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Data Base for Standards/Regulations Development for Land Disposal of Flue Gas Cleaning Sludges

SCS Engineers, Long Beach, Calif

Prepared for

Municipal Environmental Research Lab, Cincinnati, Ohio Solid and Hazardous Waste Research Div

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This study addresses the problem of flue gas cleaning (FGC) sludge disposal to the land. It considers the problem from a potential regulatory approach, looking at the various aspects which could play a part in determining the best practical control technology currently available. Factors that were taken into consideration include: (1) the origin of the FGC sludge problem (character of the fuel, combustion process, gas cleaning and sludge management); (2) criteria for the evaluation of sludge disposal options (sludge characteristics, health, ecological, safety, and aesthetic considerations; (3) applicable, existing or proposed standards/regulations (solid waste, hazardous waste, drinking water, and air pollution regulations); and (4) impacts of applying existing standards/regulations to the disposal of flue gas cleaning sludges (cost aspects). The report presents 14 conclusions supporting the need for FGC sludge disposal regulations and suggests a decision tree approach to the formulation of guidelines and limitations for FGC sludge management which takes into account site specific geographical and hydrological considerations. The report contains 179 references and an Appendix on The Equations of Mass Transport.

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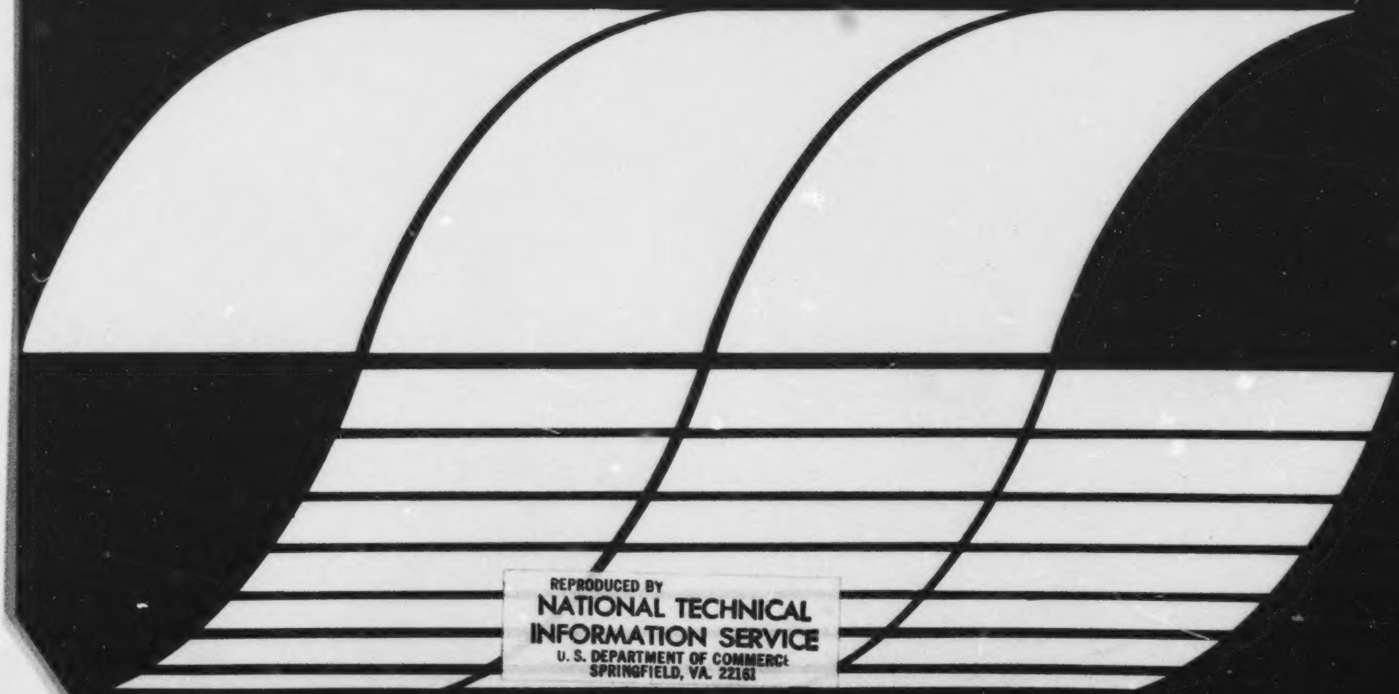

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December 1977

DATA BASE FOR STANDARDS/REGULATIONS DEVELOPMENT FOR LAND DISPOSAL OF FLUE GAS CLEANING SLUDGES

by

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> "The Office of Solid Waste believes that scrubber sludge should not be landfilled unless the sludge is solid. This will normally require chemical treatment of the sludge except in special situations (such as a desert) where the sludge will dry out. If the sludge remains wet indefinitely, the disposal area will be useless for additional use and this should not be acceptable. Long term land degradation that is reasonably avoidable should not be a tradeoff of air pollution control."

FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This report presents a decision tree approach to the formulation of guidelines and limitations for Flue Gas Cleaning (FGC) sludge management which takes into account site specific geographical and hydrological considerations. The information is applicable to the problem of safely disposing of wastes on land.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

This study addresses the problem of flue gas cleaning (FGC) sludge disposal to the land. It considers the problem from a potential regulatory approach, looking at the various aspects which could play a part in determining the best practical control technology currently available. Factors that were taken into consideration include: (1) the origin of the FGC sludge problem (character of the fuel, combustion process, gas cleaning, and sludge management); (2) criteria for the evaluation of sludge disposal options (sludge characteristics, health, ecological, safety, and aesthetic considerations; (3) applicable, existing or proposed standards/regulations (solid waste, hazardous waste, drinking water, and air pollution regulations); and (4) impacts of applying existing standards/regulations to the disposal of flue gas cleaning sludges (cost aspects). The report presents 14 conclusions supporting the need for FGC sludge disposal regulations and suggests a decision tree approach to the formulation of guidelines and limitations for FGC sludge management which takes into account site specific geographical and hydrological considerations. The report contains 179 references and an Appendix on The Equations of Mass Transport.

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SECTION I

CONCLUSIONS

1. Existing air pollution control regulations limit the quantity of SO_x that can be discharged by fossil fueled power plants and other industries. One option available for SO_x removal is flue gas desulfurization (FGD) processes, in which various designs of scrubbers use calcium or other sorbants to react with the SO_x. These scrubbers generate large quantities of FGD sludge, and the proper management of this sludge is of national environmental concern.

2. Based upon an estimated 0.5 million t/1000 MW capacity (at 70 percent load factor) of FGD sludge generation, projected FGD sludge quantities are:

	Year		
	1975	1980	1985
Number of FGD scrubber units	14	64	72
Total power capacity, MW	2,500	23,000	27,000
FGD sludge generated annually in thousand metric tons of dry solids	1,225	11,200	13,300

An additional 10 percent (approximately) of the installed FGD systems use supplementary processes to convert the recovered wastes into marketable by-products. Unfortunately, the economic feasibility is currently unfavorable in the U.S., so throwaway sludge methods are expected to dominate industries.

3. Consideration was given to the subcategorization (for regulatory purposes) of plants generating FGD sludge. The physical and chemical characteristics of raw FGD sludge are influenced by many, often interrelated, in-plant variables, including:

- Fuel type and composition
- Boiler type, design, and operation

- Fly ash and bottom ash removal systems and their relation to sludge disposal

- FGD system type, design, and operation

- FGD reagent and input water quality

The effects of these variables upon the characteristics of the raw FGD sludge generated are complex and difficult to predict. In addition, plants may often change fuel and/or operational procedures, thereby changing the FGD sludge characteristics. Therefore, it is deemed impractical to regulate FGD sludge disposal on the basis of type of plant or in-plant process. As stated later in these conclusions, regulation for FGD sludge treatment and disposal should be based, instead, upon analysis of disposal site characteristics.

4. The physical and chemical characteristics of FGD sludge are important to effective management and are the subject of most disposal-related research efforts to date. Biological characteristics of the sludge are expected to be of limited importance since the waste is inorganic; research in this area is lacking.

FGD sludge solids typically contain four major constituents: calcium sulfate dihydrate, calcium sulfite hemihydrate, unreacted sorbent, and fly ash. The solid phase of FGD sludge also contains a variety of trace metals and mixed sulfite/sulfate crystals. The liquid phase of FGD sludge usually contains ions of sulfate, sulfite, calcium, and various trace chemical species. The total dissolved solids (TDS) concentration in the liquor is a function of the equilibrium levels of solids in the scrubber system. TDS concentration in closed-loop operations is typically 15,000 to 20,000 ppm.

Physical characteristics of FGD sludge vary widely depending primarily upon:

- The ratio of sulfate to sulfite in the FGD sludge;

- The size and shape of the crystals; and

- The quantity of fly ash and/or bottom ash contained in the FGD sludge.

Predominantly sulfite sludges are more unstable (often thixotropic) and difficult to dewater than predominantly sulfate sludges. The addition of fly ash and possibly bottom ash can improve the stability of sulfite sludges, sometimes by one or two orders of magnitude.

5. Current FGD sludge treatment and disposal practices are listed in Table 1. The typical operations are:

TABLE 1. CURRENT FGD WASTE MANAGEMENT PRACTICES IN THE U.S. (JUNE 1977)

Process	No. of Operating Units Industrial	Utility
Treatment		
Dewatering		
. Clarifier/thickener	6	32
. Vacuum filter	6	10
. Centrifuge		4
Stabilization		
. Commercial	0	6
. Other*	2	5
Transportation		
Pipe	1	35
Truck/rail	6	7
Disposal		
Pond (unlined)	1	6
Pond (lined)†	1	22
Landfill	6	8
Mine	0	1

* Either continuous or intermittent codisposal with fly ash and/or bottom ash after dewatering mechanical

† With either natural low permeability material or similar "foreign" materials

- Initial dewatering in a clarifier thickener;
- Secondary dewatering with a vacuum filter or centrifuge;
- Stabilization by addition of ash (with dewatering) and/or commercial additives;
- Pipeline transportation to the disposal site; and
- Disposal into a pond or landfill.

Initial dewatering is virtually universal because it reduces sludge volume, conserves water, and improves handling characteristics. Secondary dewatering is generally used if it is desired to further reduce volume prior to truck transport or commercial stabilization treatment.

The stabilization of sludge is designed to improve structural stability and decrease contaminant mobility. Stabilization can be performed by one of several commercial processes or by addition of ash, soil, or some other stabilizing additive.

Sludge is usually transported to the disposal site by pipeline. Truck transport of sludge is used when:

- The sludge is too thick to pipe, which is the case after secondary dewatering or stabilization;
- The sludge is removed to a distant disposal site; or
- Less expensive alternatives are otherwise infeasible.

Existing FGD sludge disposal methods include the use of ponds (lined or unlined) or landfills to contain the sludge. To date, most power plants have used ponds, while most other industries have used landfills because their sludge volumes are relatively low. Ocean and mine disposal are under study but are not being practiced.

6. Important considerations when evaluating the potential health effects of sludge contaminants are: (1) the pathways to man, and (2) the concentrations at the point of exposure. The pathways of interest are groundwaters and surface waters. The transport of contaminants via groundwater is a complex mechanism, involving a storage function in the soil and dilution in the aquifer. Each contaminant has its own time constant for transport based upon the two previously mentioned considerations. Surface water contamination can be caused by either intentional liquor discharge (although not practiced) or accidental release of sludge suspensions.

Limited studies of sludge leachate and surface water discharges have concluded the following:

- All studies agree that the total dissolved solids in the sludge liquors exceed drinking water standards;
- All studies indicate that the selenium concentration commonly exceeds drinking water standards;
- Some data indicate that fluoride concentrations may be high;
- All studies indicate that arsenic, lead, and mercury (among other) concentrations can exceed drinking water standards in some instances, although these concentrations are typically below standards and are readily attenuated by most soils.

7. Important disposal site characteristics are: present and projected land use, topography, hydrogeology, and meteorology. Projected land use is an important consideration, particularly in urban areas where land value is high. Treatment/disposal techniques that utilize less land space and/or generate a fill material with adequate bearing strength are often cost effective in urban areas.

Topography of the disposal area influences the potential impact of the disposal operation. Sludge retention structures (dikes, dams, etc.) should be fail-safe in areas where sludge could flow to nearby surface waters. The relative elevation of the pond surface, the pond bottom, and the groundwater affect mass transport of sludge contaminants and dissolved solids.

Site hydrogeology is of major concern to regulatory agencies, as it controls the mass transport of contaminants to the surrounding environment. Important hydrogeologic parameters are site permeability, hydraulic potential, and groundwater characteristics. These parameters, coupled with estimates of attenuation and ion exchange in the soil, can provide an estimate of contaminant mass transport rate and mixing with the groundwater.

Local meteorology interacts with the disposal technique through the evaporation/precipitation ratio and wind erosion potential. The evaporation/precipitation ratio controls the concentration of salts in the leachate and the hydraulic potential above the groundwater.

8. Safety considerations associated with the disposal of FGD sludges can be directed toward: (1) workers employed at the site; (2) the general public; and (3) livestock and wild animals. These safety considerations relate to the unstable

properties of certain FGD sludges. Safety problems can be alleviated by worker awareness and limited access to the disposal area.

9. Ecologically, if the sludge should accidentally be discharged in large quantities to flowing water courses, it could have a catastrophic effect upon surface water biota. Since sulfite-bearing sludges have a high COD, the contents of a large pond could theoretically deplete the oxygen in a major waterway for a considerable distance.

10. The aesthetic impact of an FGD sludge disposal site is site specific. The impact is highly dependent upon the proximity of the site to the public, which determines whether the operation can be seen and heard. It is presumed that local ordinances can sufficiently regulate heavy construction work. After decommissioning of the site, proper soil cover and landscaping should be implemented.

11. Parameters that regulate chemical and physical characteristics of the FGD sludge were evaluated. The significant chemical characteristics are the liquid phase concentrations of TDS, boron, fluoride, mercury, lead, and selenium. The selection of a regulating parameter from among these components should satisfy the following criteria:

- Accurate correlation with environmental impacts;
- Usefulness as an indicator of the migration of many contaminants, aside from itself;
- Simplicity of measurement;
- High measurement accuracy and reproducibility; and
- Low analytical cost.

Of the contaminants listed, TDS provides the best indication of overall contaminant migration, due to limited attenuation and ion exchange. TDS is also the simplest and least expensive contaminant to measure. In view of these considerations, it is concluded that TDS is the best chemical regulating parameter for FGD sludge disposal. While TDS should be used to monitor contaminant migration, concentrations of other contaminants should also be measured in the leachate to confirm the mass transport calculations.

The physical properties of FGC sludges are important to the following disposal site considerations:

- Future land use;

- Rate of mass transport of contaminants from the site, as a factor of in-place sludge permeability; and

- Sludge flow during accidental release (particularly to a flowing stream).

Physical characteristics relating to these considerations include load-bearing strength, viscosity, and permeability. How many, if any, of these characteristics are important to a particular site are site-dependent.

It was concluded that characteristics of FGD sludge set need for regulation. Regulations should allow for site-specific factors as well as sludge characteristics.

12. Only fragmented disposal cost information was available for inclusion in this report. In some instances, the information was based on minimal actual engineering cost estimates. Studies presenting cost estimates thus far have concentrated upon stabilization costs, transport costs, and costs of final disposal operations. Detailed engineering cost information on FGD sludge disposal should be available in mid 1977 from a recently completed study by TVA.

13. State solid waste disposal and water quality standards have most frequently been applied to FGD sludge disposal on state and local levels. State solid waste disposal regulations often include consideration of: (1) groundwater protection; (2) protection of the site from floods; (3) rainfall runoff control; and (4) site reclamation.

Quantitative specifications applicable to FGD sludge disposal for control measures are available from other state and federal regulations, such as those concerning:

- Hazardous waste disposal;
- Wastewater disposal;
- Water quality criteria for various beneficial uses;
- Comprehensive air quality criteria;
- Waste disposal to oceans; and
- Waste disposal to mines.

Several hazardous waste disposal regulations and guidelines are particularly applicable to FGD sludge disposal. Dam construction guidelines for phosphate slime ponds are enforced by the state of Florida, where most phosphate mining is performed. Similarly, acid mine drainage sludge ponds are subject to federal regulations for impounding structures. The disposal of gypsum from phosphoric acid manufacture is similar to that of FGD sludge; applicable regulations include runoff control and impoundment construction.

14. Consideration was given to development criteria for guidelines for FGD sludge disposal. Based upon the data base compiled in this study, it was concluded that potential environmental impacts from FGD sludge disposal can be identified, and a conceptual approach to their control can be developed.

The most appropriate regulatory approach may be one that takes into account the site variables and their effect on environmental impact. The suggested approach consists of:

(1) Establishment of environmental resources to be protected and beneficial uses (if any) of the disposal site;

(2) Determination of the degree of regulation necessary to protect the environmental resources;

(3) Categorization of treatment/disposal system capability to provide necessary environmental protection; and

(4) Establishment of monitoring, control, and reporting procedures.

When defining beneficial uses of a site, the regulatory agency determines the environmental resources to be protected. These resources may include groundwater resources underlying the site, surface water resources, and future land use.

The acceptability of the proposed disposal site is estimated, based upon natural site characteristics and sludge characteristics. A simplistic system of subcategorizing sites as a function of their beneficial uses is presented in Figure 1. This "decision tree" uses the following site variables as decision points:

- Possible future land use;
- Groundwater resources;
- Evaluation of natural protection to groundwater resources afforded by site geology and hydrology;
- Surface water protection from catastrophic events; and
- Site meteorology.

The output of this decision tree is an assigned site category that defines what control technology is necessary to protect the given environmental benefits. The numbers selected for the decision points are subjective, due to the nebulous legal definitions of degradation and the future value of land.

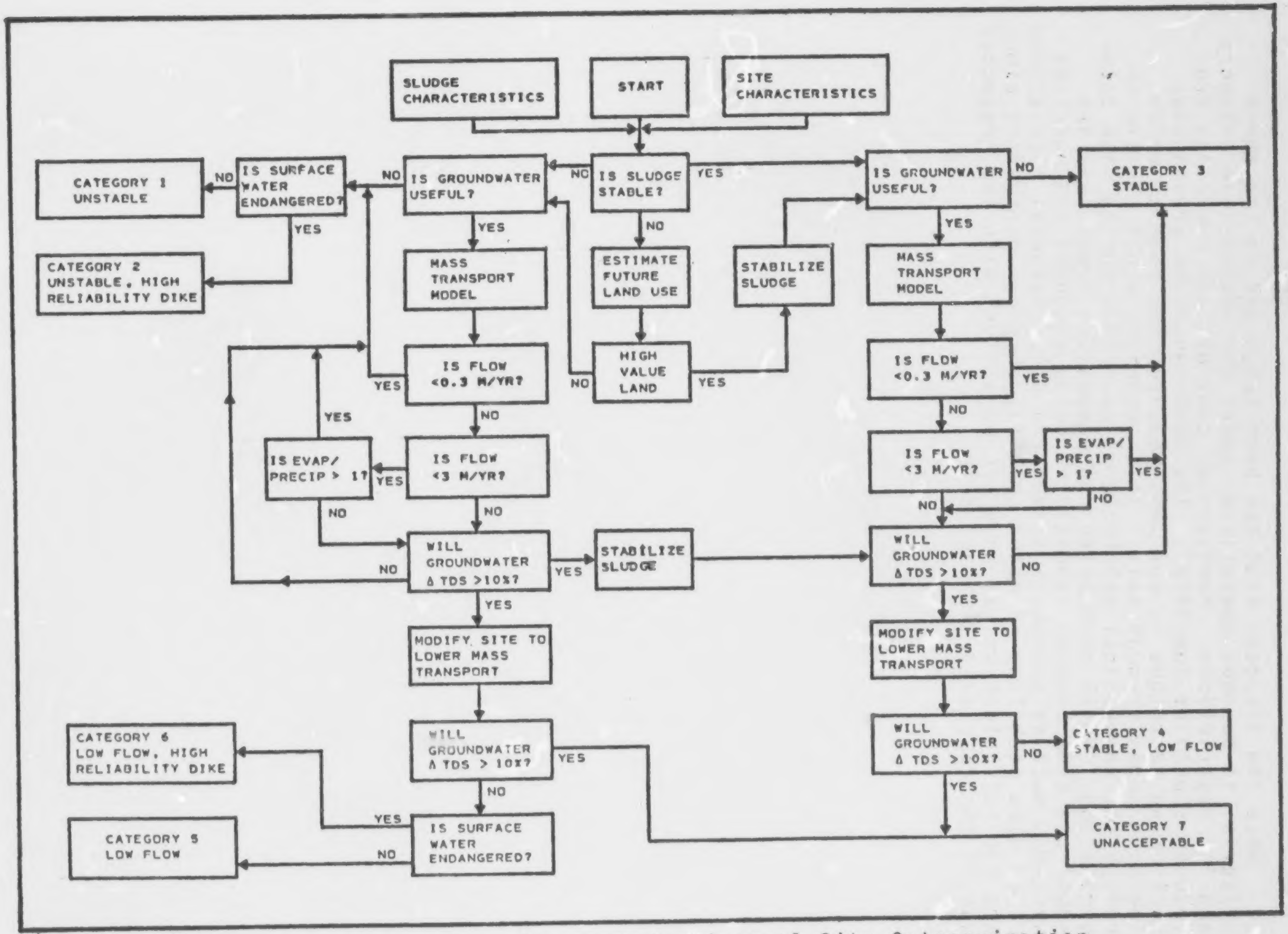
SLUDGE CHARACTERISTICS
START
SITE CHARACTERISTICS
IS SLUDGE STABLE?
YES
NO
IS GROUNDWATER USEFUL?
NO
IS SURFACE WATER ENDANGERED?
NO
CATEGORY 1 UNSTABLE
YES
CATEGORY 2 UNSTABLE, HIGH RELIABILITY DIKE
YES
MASS TRANSPORT MODEL
IS FLOW <0.3 M/YR?
YES
NO
IS FLOW <3 M/YR?
YES
IS EVAP/ PRECIP > 1?
YES
NO
NO
WILL GROUNDWATER Δ TDS >10%?
NO
YES
STABILIZE SLUDGE
YES
MODIFY SITE TO LOWER MASS TRANSPORT
WILL GROUNDWATER Δ TDS > 10%?
YES
NO
IS SURFACE WATER ENDANGERED?
YES
CATEGORY 6 LOW FLOW, HIGH RELIABILITY DIKE
NO
CATEGORY 5 LOW FLOW
NO
ESTIMATE FUTURE LAND USE
HIGH VALUE LAND
NO
YES
STABILIZE SLUDGE
IS GROUNDWATER USEFUL?
NO
CATEGORY 3 STABLE
YES
MASS TRANSPORT MODEL
IS FLOW <0.3 M/YR?
YES
NO
IS FLOW <3 M/YR?
YES
IS EVAP/ PRECIP > 1?
YES
NO
NO
WILL GROUNDWATER Δ TDS >10%?
NO
YES
MODIFY SITE TO LOWER MASS TRANSPORT
WILL GROUNDWATER Δ TDS >10%?
NO
CATEGORY 4 STABLE, LOW FLOW
YES
CATEGORY 7 UNACCEPTABLE

Figure 1. Decision Tree Approach to Disposal Site Categorization

Once the disposal site has been subjected to the above criteria, it becomes operational under the appropriate category and its restrictions. Monitoring, control, and reporting procedures should be specified. The most important groundwater monitoring technique is one that measures the rate at which leachate moves through soil. This technique would confirm or refute the theoretical calculations performed during site categorization. Spill monitoring and prevention procedures are available from several specialized waste disposal and handling systems, such as phosphate slimes and oil. Disposal regulations based upon stability or other specific physical parameters alone are not sufficient unless they are consistent with the projected use of the completed disposal site.

SECTION II

RECOMMENDATIONS

1. Substantial additional FGD research is currently under way or planned by both EPA and industry programs. The data base presented in this report should be periodically updated to include new research results.

2. A key conclusion of this report is that characteristics of FGD sludge set need for regulation. Regulations allow for site-specific factors. In order for state and local regulatory officials to regulate properly, specific information will be required:

(a) Geohydrological survey of proposed disposal site locations;

(b) Mass transport of contaminants from the disposal site into groundwater under various conditions of geology, hydrology, FGD sludge characteristics, disposal site design, climate, and other factors;

(c) Engineering design standards for retention structures, secondary retention safeguards, drainage structures, and accessories associated with FGD disposal ponds;

(d) Sludge characteristics required as a function of future use for the site. Guidelines are required to correlate future stability, bearing capacity, etc. of various types of in-place FGD sludge with desired future land uses;

(e) Techniques to allow monitoring of contaminant mass transport from the disposal site through the underlying soil; and

(f) Value analysis of allowable groundwater degradation vs. disposal operation cost; e.g., is a rise in groundwater TDS concentration of 20 mg/ℓ in x m^3 of water acceptable in exchange for a savings of $5/ton in FGD sludge disposal cost? Consideration must be given to the time scale involved and the impossibility of zero discharge.

Aspects of the above listed guidelines are being researched.

3. Detailed study is suggested specifically to identify the various disposal advantages and disadvantages of calcium sulfite and calcium sulfate in terms of the various environmental impact criteria set forth under "Conclusions."

4. If regulations are deemed necessary, the site-specific regulatory approach shown in Appendix A is suggested. This approach is based upon (1) a preliminary assessment of potential environmental impacts from all disposal aspects, followed by (2) a monitoring program to cross-check this assessment against actual events.

In cases where a particular disposal operation will not degrade local groundwaters or surface waters due to their already poor quality, it is important that baseline "normal and reasonable" disposal precautions be established and practiced nonetheless.

SECTION III

INTRODUCTION

PURPOSE AND AUTHORITY

On December 23, 1971, the U.S. Environmental Protection Agency, under the authority of the Clean Air Act of 1970, promulgated regulations on standards of performance for new stationary sources of air pollution. The regulations provided air pollution emission limits for a variety of stationary source categories, and called upon the states to establish compliance schedules using emission limits at least as stringent as the federal standard.

Specifically, subpart D established Standards of Performance for Fossil-Fuel Fired Steam Generators of more than 63 million kcal per hour heat input (250 million Btu per hour). These standards became effective on August 17, 1971. Section 60.43 established the standards for sulfur dioxide emissions at (1) 1.4 g per million cal heat input (0.8 lb per million Btu) derived from liquid fossil fuels and (2) 2.2 g per million cal heat input (1.2 lb per million Btu) derived from solid fossil fuels.

On September 10, 1973, the U.S. Court of Appeals for the District of Columbia remanded to EPA certain of the new source standards as they apply to power plants. In particular, the court stated that EPA had not satisfactorily addressed the problem of by-product sludge disposal from wet scrubbing flue gas desulfurization (FGD) systems. These lime, limestone, and double alkali slurry scrubbing processes were denoted as the anticipated "best system" for standard compliance by high sulfur fuel users. The major areas of concern were (1) the necessity of disposing of large quantities of solid wastes; (2) possible surface and groundwater contamination; and (3) possible degradation of large areas of land by certain untreated sludges. In its response to remand (November 12, 1974), EPA recognized the problem of FGD sludge disposal and the care which must be taken in selecting an environmentally acceptable disposal method. Chemical treatment of FGD sludge was recommended as most environmentally acceptable.

Beginning in 1972, EPA initiated a major study program aimed at fully assessing the extent of the FGD sludge disposal problem. This report is the product of a one-year study of related research findings generated by the EPA study program.

OBJECTIVE AND APPROACH

The primary objective of this study is to organize the existing data base to assist the future development of disposal regulations/standards and to suggest research needs in related areas. The purpose is: (1) to establish a data base reflecting the present state of knowledge for the environmentally-acceptable disposal of FGD sludges, and (2) to evaluate the completeness of this data base to support the formulation of related regulations/standards for the disposal of FGD sludge. The data base includes the environmental aspects of sludge disposal, state-of-the-art disposal technologies, proposed or existing standards/regulations which could have a bearing on FGD sludge disposal, and the impact of applying these standards/regulations. The data base evaluation is intended to provide a basis for assessing the potential for environmental degradation imposed by desulfurization sludges, and for determining the extent to which existing technologies can cope with or avert this problem.

This study is one of 17 currently under way as part of the EPA's Energy Research Program entitled "Control of Waste and Water Pollution from Flue Gas Cleaning Systems." The major aims of the program are: (1) to establish an understanding of the environmental impact associated with sludge disposal, and (2) to evaluate the available technology and associated economics necessary to limit degradation of the environment. The following is a list of current projects and the organizations responsible for each:

Environmental Assessment of FGD Waste Disposal

1. FGC Waste Characterization, Disposal Evaluation and Transfer of FGC Waste Disposal Technology (Aerospace Corporation).

2. Shawnee FGD Waste Disposal Field Evaluation (Tennessee Valley Authority (TVA)).

3. Louisville Gas and Electric Evaluation of FGD Waste Disposal Options (Louisville Gas and Electric).

4. Lime/Limestone Wet Scrubbing Waste Characterization (TVA).

5. Lab and Field Evaluation of First and Second Generation FGC Waste Treatment Processes (U.S. Army Corps of Engineers - Waterways Experiment Station (WES)).

6. Characterization of Effluents from Coal - Field Power Plants (TVA).
7. Ash Characterization and Disposal (TVA).
8. Studies of Attenuation of FGC Waste Leachate by Soils (U.S. Army Materiel Command).
9. FGC Waste Leachate-Liner Compatibility Studies (WES).
10. Establishment of Data Base for FGC Waste Disposal Standards Development (SCS Engineers).
11. Environmental Effects and Control of Various Flue Gas Cleaning (FGC) Sludge Disposal Options (SCS Engineers).

FGD Waste Disposal Economics

1. Conceptual Design/Cost Study of Alternative Methods for Lime/Limestone Scrubbing Waste Disposal (TVA).
2. Shawnee FGD Waste Disposal Field Evaluation (Tennessee Valley Authority (TVA)).
3. Environmental Effects and Control of Various Flue Gas Cleaning (FGC) Sludge Disposal Options (SCS Engineers).

Alternate Disposal Methods

1. Evaluation of Alternative FGD Waste Disposal Sites (A. D. Little, Inc.).
2. Environmental Effects and Control of Various Flue Gas Cleaning (FGC) Sludge Disposal Options (SCS Engineers).

FGD Waste Utilization

1. Gypsum By-Product Marketing Studies (TVA).
2. Fertilizer Production Using Lime/Limestone Scrubbing Wastes (TVA).
3. Lime/Limestone Scrubbing Waste Conversion Pilot Studies (currently under negotiation).

Power Plant Water Use

1. Assess/Demonstrate Power Plant Water Reuse/Recycle (Radian Corporation).

This study was approached in two phases, as dictated by its dual purpose. Phase I was establishment of the environmental, technological, and legal data base, and consisted of four principal tasks: (1) development of a detailed work plan for EPA approval; (2) establishment of the criteria necessary to evaluate existing disposal options; (3) compilation of existing or proposed standards/regulations which could have a bearing on the disposal of FGD sludges; and (4) evaluation of the impact of applying Task 3 standards/regulations to the present sludge disposal problem. The Phase II effort organized Phase I results into an information base for the future development of standards and consisted of the following tasks: (1) development of a detailed work plan for EPA approval; (2) analysis of the interrelationships between environmental effects and regulatory approaches; (3) development of a technical basis for future standards development; and (4) identification of research and development needs.

GENERAL BACKGROUND

The combustion of sulfur-bearing compounds to produce by-product sulfur oxides (SO_2, SO_3) occurs on a large scale in several industries including petroleum refining, non-ferrous metal smelting, sulfur and sulfuric acid manufacture, and fossil fuel combustion to produce steam and electric power. Of these sources, fossil fuel (particularly coal) combustion most often encounters the problem of throwaway sludge disposal.

The alternatives available for compliance with air emission standards are: (1) to burn fuels of sufficiently low sulfur content, (2) to burn higher sulfur fuels and remove the sulfur oxides from the exhaust gas, or (3) to use alternative combustion technologies. Selection of the first alternative precludes the need for FGD. The second alternative permits the use of a wide variety of fuels, but usually necessitates the use of some type of wet scrubbing FGD system. The third alternative is only now achieving commercial availability.

Flue gas desulfurization (FGD) refers to any system, wet or dry, which removes sulfur oxides from exhaust gases. This is contrasted with flue gas cleaning (FGC), which for the purposes of this study refers to any system which removes particulate and/or gaseous air pollutants from exhaust gases. The FGC systems of interest here are those which collect: (1) sulfur oxides alone, or (2) sulfur oxides and fly ash simultaneously. For this reason, FGD and FGC are often used interchangeably throughout this report.

The technology of flue gas cleaning for SO_x control has advanced rapidly in the last ten years. Consequently, a variety of wet scrubbing systems have become available for the removal of SO_2 from power plant flue gas. Sorbents commonly used in wet scrubbing include lime, limestone, and sodium salts. The choice of a sorbent is dependent on several considerations including: cost, reactivity, amount of preparation required, and dissolution rate. Lime and limestone are both effective and inexpensive and currently most popular. Other alkali sorbents are gaining favor.

FGC throwaway sludges are most easily classified as sulfate, sulfite, or double alkali. Calcium sulfate and calcium sulfite are the predominant components of the first two, while the third contains a fractional amount of sodium sulfate loss from the regeneration system. All three types may contain varying amounts of fly ash, depending upon particulate control equipment removal efficiency.

Table 2 displays the relative amounts of fly ash, bottom ash, and FGD sludge generated and disposed of at a hypothetical 1,000-MW power plant.

PROJECTIONS

Table 3 displays the total existing (1975) and projected non-regenerable FGD capability in the U.S. through 1985. These figures are based upon information in the December 1976 PEDCO summary report of FGD systems (Ref. 123). "Committed" systems are those plants which have at least signed a letter of intent to install FGD. Regenerable FGD systems presently account for less than 10 percent of the total installed capacity and should continue at this level through 1985.

More detailed projections of FGD installations are presented later in this report.

TABLE 2. COMPARISON OF FGD SLUDGE PRODUCTION WITH PRODUCTION OF OTHER WASTE MATERIALS

Waste	Percent Solids	Total Tonnage, 1,000 MW Power Plant*	Total Annual Production (year)**
FGD Sludge	25	250,186	64,000,000 (1980)
	50	125,093	
Fly Ash	25	117,734	
	100	29,433	95,000,000 (1980, 80% solids)
Bottom Ash, Slag	25	1,059,609	
	100	264,902	
Municipal Refuse	75	--	360,000,000 (1973)
Municipal Sewage Sludge	0.1-20.0	--	55,000,000 (1980)
Phosphate Rock Slime	4-6	--	760,000,000 (1970)
Acid Mine Drainage Sludge	1-5	--	8,200,000 (1973)
Gypsum from Fertilizer Manufacture	85-90	--	28,000,000 (1973)

*Model Plant Assumptions

Coal: 3% S
12% Ash
Boiler Type: Cyclone
Load Factor: 70%

Scrubber Efficiency: 85%
Sludge Production: 0.082 metric tons sludge/metric ton coal

0.4 Kg coal/kwh
Fly ash production = 12 kg/metric ton coal

**Ref. 129.

TABLE 3. COMMITTED AND PROJECTED NON-REGENERABLE FGD CAPABILITY, 1975-1985 (MW)*

	Lime Scrubbing	Limestone Scrubbing	Lime/ Limestone	Double Alkali	Total Committed	Total Projected
1975	475 (2)	1,954 (9)	20 (2)	32 (1)	2,481 (14)	---
1980	9,445 (23)	12,695 (35)	270 (3)	902 (4)	23,312 (65)	35,000
1985	11,515 (28)	13,445 (37)	797 (4)	†	26,659 (73)	100,000

* Numbers in parenthesis indicate number of scrubber units

† None committed beyond 1980

Ref. 123

SECTION IV

INDUSTRY CATEGORIZATION

DESCRIPTION OF POWER GENERATING FACILITIES

In 1977, there are 1040 fossil fuel fired power plants operating in the United States, possessing a combined generating capacity of more than 320,000 megawatts. By 1994, 200 more plants with an additional 111,041 megawatts of generating capacity are projected to become operational. Of this 1994 capacity, 66 percent will fire coal exclusively. The remainder will use oil, natural gas, or a combination of oil and coal (Ref. 138). Oil will decline in popularity because of both uncertainty of supply and expected rising costs from foreign sources. Domestic coal use will increase due to its ready availability and autonomy from foreign control. Coal use will also rise due to the current administration policy on energy.

Under the federal Clean Air Act, power plants are responsible for emission control. For control of sulfur oxide emissions, the two most widely used methods are:

(1) The use of a natural low sulfur fuel or partially desulfurized high sulfur fuel; and

(2) Flue gas desulfurization (FGD).

Existing oil-fired plants can convert with relative ease to low sulfur oil if it is available. Coal-fired boilers, however, have difficulty in converting to low sulfur coals due to differences in heating value, percentage ash, and other fuel characteristics.

Most coal-fired generating plants are in the heavily populated eastern sector of the United States. Coal supplies in these regions are for the most part high sulfur bituminous and subbituminous varieties. The scarcer low sulfur eastern coals are in great demand for metallurgical use, and hence are more expensive than higher sulfur coal. Long distance transport of low sulfur western coal may be less economically feasible than FGD installation. Consequently, the majority of installed FGD units are in the eastern United States. However, stringent state SO_x standards in the west may also cause increased FGD use in that area.

Non-regenerable processes account for approximately 90 percent of those FGD systems which are either operational or under construction. Lime and limestone systems are the most prevalent, with 75 percent of the scrubbers projected to be operational by 1980 utilizing these processes (Ref. 65).

The sodium-lime double-alkali systems thus far have been installed primarily on industrial fossil fuel fired boilers. However, interest in the double-alkali process is increasing due to difficulty with mist-eliminator pluggage in certain lime/limestone systems. Recently, Gulf Power Company completed testing of a double-alkali system on a 20-MW plant at its Scholz Station. Central Illinois Public Services' 600-MW Newton plant will be operating the only utility scale double-alkali system when it comes on line in December 1977. Louisville Gas and Electric is building a 250-MW system at Cane Run under partial EPA sponsorship.

Scrubber systems regenerating sulfur or sulfuric acid have not yet gained very much acceptance in the United States. Only four full-scale projects are still in the active planning stages, while two others were shut down due to acid marketing problems. These are:

- Wellman-Lord/Allied Chemical process at the San Juan station of New Mexico Public Service
- EPA's demonstration project with Wellman-Lord/Allied Chemical process at the Mitchell station of Northern Indiana Public Service
- United Engineers magnesia oxide process at the Philadelphia Electric Eddystone station

DESCRIPTION OF INDUSTRIAL FGD USERS

Many non-utility industrial scale fossil fuel fired steam generators are also regulated by the new source standards. Most smaller boiler units are equipped for firing a variety of fuels and have achieved compliance by use of low sulfur fuels.

A total of eight non-regenerable industrial scale FGD systems will be on line by June 1977 in the United States. As seen in Table 4, non-regenerable double-alkali FGD is the system prevalent for industrial steam generators. The table also shows that landfill is the most common means of sludge disposal by industrial FGD users.

LOCATION OF FGD USERS

Figure 2 displays the locations of operational non-regenerable FGD systems (both utility and industrial) in the United States as of June 1977.

TABLE 4. INDUSTRIAL FGD APPLICATIONS AND THEIR SLUDGE DISPOSAL METHODS*

System Operator	MW or Equivalent	FGD Process	Scrubber Type	Disposal Method
FMC				
Modesto, CA	10	Double Alkali	Packed bed	Landfill
Green River, WO	150	Sodium Carbonate	FDS**	Lined pond
General Motors				
Parma, OH	32	Double Alkali	Adsorber trays	Unlined pond/ Landfill
Caterpillar Tractor Co.				
Joliet, IL	20-30	Double Alkali	Venturi	Landfill
East Peoria, IL	100	Double Alkali	Venturi	Landfill
Mossville, IL	45-55	Double Alkali	Venturi	Landfill
Firestone				
Pottstown, PA	3	Double Alkali	Venturi	Landfill
Alyeska				
Valdez, AK	13	Sodium Carbonate	FDS**	

* As of June 1977

**FDS - Flood Disc Scrubber

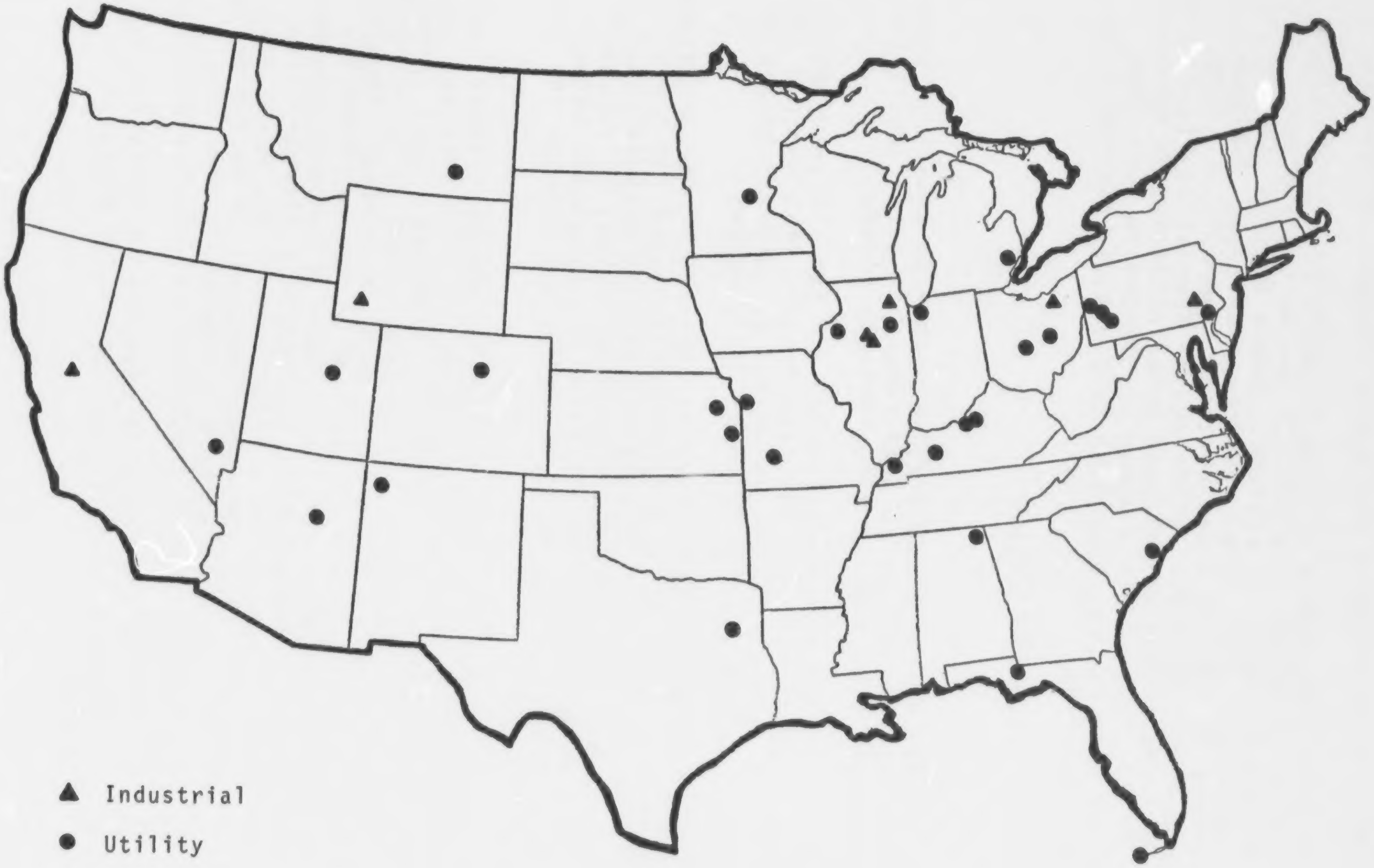
▲ Industrial
● Utility

Figure 2. Location of Industrial and Utility Plants in the United States Utilizing Sludge Generating FGD Units

EXISTING UTILITY FGC SYSTEMS AND SLUDGE DISPOSAL OPERATIONS

As of June 1977, there will be 41 operational FGD units installed on utility scale boilers in the United States. Table 5 locates and describes these systems. Table 6 gives the details of their associated FGD sludge management systems. The information contained in the table was obtained from both the July-August 1976 report by PEDCO Environmental Specialists (Ref. 123) and an SCS phone survey of selected power utilities in November-December 1976. Systems are subject to changes in fuel type, scrubber bed packing, recirculation loop status, and the extent of sludge dewatering.

RATIONALE FOR SUBCATEGORIZATION

General

The purpose of subcategorization within an industry category was to take into account basic differences in waste generation, treatment technology, and economics between plants.

When discussing subcategorization for FGD sludge disposal regulation purposes, some of the same factors that entered subcategorization during effluent guideline development should be considered, but with several important differences.

The most important difference is that FGD sludge is disposed to land disposal sites and the characteristics of the specific disposal site are the most important factor in protection of the environment. For this reason, it is more logical to subcategorize FGD sludge disposal on the basis of variations between disposal sites than on the basis of variations between the plants which generate the FGD sludge.

The second major consideration in FGD sludge disposal subcategorization is that the power industry is a utility and its economics are regulated by governmental agencies. Cost increases are passed on to the consumer. Therefore, there is no rationale for subcategorization by differences in micro-economic impact. Each disposal operation must be designed on the basis of the most cost-effective method which will provide adequate protection to the environmental resources at the specific disposal site being considered. It would be a disservice to the power utility consumer to create an arbitrary subcategorization on the basis of "ability to pay," which has been necessary in some other industries to prevent economic inequities and plant closures.

An elaboration on the use of disposal site variables for implementing regulatory controls for FGD sludge disposal is provided in Appendix A.

TABLE 5. DESCRIPTION OF OPERATIONAL UTILITY FGD SYSTEMS

Power Station		Plant Size MW	Fuel Characteristics				Particulate Control Device	FGD Process	
Utility	Unit		Type	BTU/lb	% S	% Ash		Sorbent	Scrubber
Arizona PU Service	Cholla No. 1	115	Coal	12,146	0.44-1	12.3	Mech.	Limestone	FGD[1], packed tower
Arizona PU Service	Cholla No. 2	250	Coal		0.44-1	10	ESP	Limestone	FSS[1], packed tower
Arizona PU Service	4 Corners No. 5A	160	Coal	8,750	0.7	22	ESP	Lime	Horizontal
Central Ill. Light Co.	Duck Creek No. 1A	100	Coal	10,300-10,500	2.5-3.0	9-10	ESP	Limestone	Venturi rod
Columbus & So. Ohio Elec.	Conesville No. 5	400	Coal	10,600	4.5-4.9	17	ESP	Lime	TCA
Commonwealth Edison Co.	Will County No. 1	167	Coal	9,463	2.1	10	ESP Venturi	Limestone	Spray tower
Detroit Edison	St. Clair No. 6	180	Coal	11,300	3.7	16	ESP	Limestone	Tray tower
Duquesne Light Co.	Elrama	510	Coal	11,000	1.0-2.8	18.2	Mech., ESP	Lime	Venturi
Duquesne Light Co.	Phillips	410	Coal	11,000	1.0-2.8	18.2	Mech., ESP	Lime	Venturi
Gulf Power Co.	Scholz Nos. 1B & 2B	23	Coal	12,400	3.0-5.0	14	ESP Venturi	Dilute acid	Spray trays Packed tower

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[1] FDS = Flooded Disc Scrubber

[2] TCA = Turbulent Contact Adsorber

Table 5 (continued)

Power Station		Plant Size MW	Fuel Characteristics				Particulate Control Device	FGD Process	
Utility	Unit		Type	BTU/lb	% S	% Ash		Sorbent	Scrubber
Kansas City Pwr. & Light	Hawthorne No. 3	140	Coal	9,800-11,500	0.6-3.0	11-14	Absorber tower	Limestone	Marble bed
Kansas City Pwr. & Light	Hawthorne No. 4	100	Coal	9,800-11,500	0.6-3.0	11-14	Absorber tower	Limestone	Marble bed
Kansas City Pwr. & Light	LaCygne No. 1	820	Coal	9,000	5.2	25	Venturi	Limestone	Sieve tray
Kansas City Pwr. & Light	Lawrence No. 4	125	Coal	10,000-12,000	0.6-3.75	10-12	Absorber tower	Limestone	Marble bed
Kansas City Pwr. & Light	Lawrence No. 5	430	Coal	10,000-12,000	0.6-3.75	10-12	Absorber tower	Limestone	Marble bed
Kentucky Utilities	Green River No. 1 & 2	64	Coal	11,000	3.8	15-25	Mech.	Lime	TCA[2]
Key West Utility Brd.	Stock Island	37	Oil		2.4-2.75		Mech.	Limestone	Venturi
Louisville Gas & Elec.	Cane Run No. 4	178	Coal	11,500	3.5-4.0	11-12	ESP	Lime	Scrubbing trains
Louisville Gas & Elec.	Paddy's Run No. 6	70	Coal	11,500	3.5-4.0	13	ESP	Lime	Marble bed
Montana Power Co.	Colstrip No. 1	360	Coal	8,800	0.8	8.83	None	Lime/alkaline ash	Venturi

[1] FDS = Flooded Disc Scrubber
[2] TCA = Turbulent Contact Adsorber

Table 5 (continued)

Power Station		Plant Size MW	Fuel Characteristics				Particulate Control Device	FGD Process	
Utility	Unit		Type	BTU/lb	% S	% Ash		Sorbent	Scrubber
Montana Power Co.	Colstrip No. 2	360	Coal	8,700	0.8/.7	8.83	None	Lime/alkaline ash	Venturi
Nevada Power Co.	Reid Gardner No. 1	125	Coal	12,450	0.5-1.0	8	Mech., Venturi	Sodium carbonate	Wash tray
Nevada Power Co.	Reid Gardner No. 2	125	Coal	12,450	0.5-1.0	8	Mech., Venturi	Sodium carbonate	Wash tray
Nevada Power Co.	Reid Gardner No. 3	125	Coal	12,450	0.5-1.0	8	Mech., Venturi	Sodium carbonate	Wash tray
No. Indiana PU Serv.	Mitchell No. 11	115	Coal	11,000	3.2-3.5	10	ESP	Sulfite/Wellman-Lord	Spray trays Packed tower
No. States Power Co.	Sherburne No. 1	710	Coal	8,300	0.8	9	Fixed-rod Venturi	Limestone/Alkaline ash	Marble bed
No. States Power Co.	Sherburne No. 2	680	Coal	8,300	0.8	9	Fixed-rod Venturi	Limestone/Alkaline ash	Marble bed
Penn. Power Co.	Bruce Mansfield No. 1	835	Coal	11,900	4.3	12.5	Adjustable Venturi	Lime	Fixed-throat Venturi
Penn Power Co.	Bruce Mansfield No. 2	835	Coal	11,900	4.3	12.5	Adjustable Venturi	Lime	Fixed-throat Venturi
Philadelphia Elec. Co.	Eddystone No. 1A	120	Coal	12,100	2.3		Mech. ESP Scrubber	Magnesium oxide	Venturi-rod

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[1] FDS = Flooded Disc Scrubber

[2] TCA = Turbulent Contact Adsorber

Table 5 (continued)

Power Station		Plant Size MW	Fuel Characteristics				Particulate Control Device	FGD Process	
Utility	Unit		Type	BTU/lb	% S	% Ash		Sorbent	Scrubber
Pub. Serv. of Colorado	Valmont No. 5	100	Coal/ gas	10,780	0.75	6-7	Absorber tower	Limestone	TCA^2
Rickenbacker AFB	Rickenbacker	20	Coal		3.6		Mech.	Lime	Spray tower
S. Carolina Publ Serv. Aut.	Winyah No. 2	140	Coal	12,500	1.08	17.2	ESP	Limestone	Venturi
Springfield City Util.	Southwest No. 1	200	Coal	12,000	3.5	13	ESP	Limestone	Modified TCA^2
Tenn. Valley Authority	Shawnee No. 10 A	10	Coal		2.9		Absorber tower	Lime/ limestone	TCA^2
Tenn. Valley Authority	Shawnee No. 10 B	10	Coal		2.9		Venturi	Lime/ limestone	Venturi Spray tower
Tenn. Valley Authority	Widows Creek No. 8	550	Coal	10,000	4-4.5	25	Mech. Venturi	Limestone	Modified TCA^2
Texas Util. Co.	Martin Lake No. 1	793	Coal	7,000	1.0	10-14	ESP	Limestone	Spray tower
Utah Power & Light Co.	Huntington No. 1	415	Coal	12,000	0.55	8.8	ESP	Lime	Vertical spray tower

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[1] FDS = Flooded Disc Scrubber
[2] TCA = Turbulent Contact Adsorber

TABLE 6. DESCRIPTION OF UTILITY FGD SLUDGE MANAGEMENT SYSTEMS

Power Station		FGD Sludge Disposal				Fly Ash Disposal	Scrubber Liquor Circulation Loop	Status[2]
Utility	Unit	Dewater[1]	Transport	Treatment	Disposal			
Arizona PU Service	Cholla No. 1	None	Pipe	None	Unlined pond	Mixed in pipe w/ sludge	Open	OP
Arizona PU Service	Cholla No. 2	None	Pipe	None	Unlined pond	Mixed in pipe w/ sludge	Open	UC
Arizona PU Service	4 Corners No. 5A	CL	Pipe	None		Disposed in closed coal mine	Closed	OP
Central Ill. Light Co.	Duck Creek No. 1A	None	Pipe	None	Unlined pond	Disposed w/sludge in common pond	Closed	UC
Columbus & So. Ohio Elec.	Conesville No. 5	CL, F		IUCS fixation	Landfill	Added to sludge in fixation	Closed	UC
Commonwealth Edison Co.	Will County No. 1	CL, F	Pipe, cement tank	Chicago fly ash fixation	Landfill	Added to sludge in fixation	Closed	OP
Detroit Edison	St. Clair No. 6	None	Pipe	None	Lined pond		Closed	OP
Duquesne Light Co.	Elrama	CL	Truck	IUCS fixation	Landfill	Mixed w/sludge in fixation	Closed	OP
Duquesne Light Co.	Phillips	CL	Truck	IUCS fixation	Landfill	Collected w/SO_2	Closed	OP

[1] CL = Clarifier
F = Vacuum Filtration
C = Centrifuge

[2] OP = Operational
UC = Under Construction, due to go on line by 6/77.

Table 6 (continued)

Power Station		FGD Sludge Disposal					Scrubber Liquor Circulation	
Utility	Unit	Dewater[1]	Transport	Treatment	Disposal	Fly Ash Disposal	Loop	Status[2]
Gulf Power Co.	Scholz Nos. 1B & 2B	CL, F		pH adj.	Ash pond	Intermittent collecting w/SO_2	Closed	OP
Kansas City Pwr. & Light	Hawthorne No. 3	CL	Pipe	None	Unlined pond	Collected w/or added to sludge	Closed	OP
Kansas City Pwr. & Light	Hawthorne No. 4	CL	Pipe	None	Unlined pond	Collected w/or added to sludge	Closed	OP
Kansas City Pwr. & Light	LaCygne No. 1	None	Rubber lined pond	None	Unlined pond	Ponded w/sludge	Closed	OP
Kansas City Pwr. & Light	Lawrence No. 4	None	Pipe	None	Unlined pond	Collected w/SO_2	Closed	OP
Kansas City Pwr. & Light	Lawrence No. 5	None	Pipe	None	Unlined pond	Collected w/SO_2	Closed	OP
Kentucky Utilities	Green River No. 1 & 2	CL	Pipe	None	Unlined pond	Collected w/SO_2	Open	OP
Key West Utility Brd.	Stock Island	CL	Pipe	None	Unlined pond	Collected w/SO_2	Open	OP
Louisville Gas & Elec.	Cane Run No. 4	CL, F	Truck, pipe	None	Landfill	Mixed w/sludge on-site	Closed	OP

[1] CL = Clarifier
F = Vacuum Filtration
C = Centrifuge

[2] OP = Operational
UC = Under Construction, due to go on line by 6/77.

Table 6 (continued)

Power Station		FGD Sludge Disposal						
Utility	Unit	Dewater[1]	Transport	Treatment	Disposal	Fly Ash Disposal	Scrubber Liquor Circulation Loop	Status[2]
Louisville Gas & Elec.	Paddy's Run No. 6	CL	Pipe	None	Landfill	Collected or added to sludge	Closed	OP
Montana Power Co.	Colstrip No. 1	CL	Pipe	None	Unlined pond	Collected w/ sludge in scrubber	Closed	OP
Montana Power Co.	Colstrip No. 2	CL	Pipe	None	Unlined/ lined pond	Collected w/ sludge in scrubber	Closed	OP
Nevada Power Co.	Reid Gardner No. 1	CL	Pipe	pH adj.	Unlined pond	Collected w/ common liquor	Open	OP
Nevada Power Co.	Reid Gardner No. 2	CL	Pipe	pH adj.	Unlined pond	Collected w/ common liquor	Open	OP
Nevada Power Co.	Reid Gardner No. 3	CL	Pipe	pH adj.	Unlined pond	Collected w/ common liquor	Open	OP
No. Indiana PU Serv.	Mitchell No. 11					Disposed in pond	Closed	UC
No. States Power Co.	Sherburne No. 1	CL	Pipe	None	Clay-lined pond	Collected w/SO_2	Closed	OP

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[1] CL = Clarifier
F = Vacuum Filtration
C = Centrifuge

[2] OP = Operational
UC = Under Construction, due to go on line by 6/77.

Table 6 (continued)

Power Station		FGD Sludge Disposal						
Utility	Unit	Dewater[1]	Transport	Treatment	Disposal	Fly Ash Disposal	Scrubber Liquor Circulation Loop	Status[2]
Penn. Power Co.	Bruce Mansfield No. 1	CL	Pipe	Dravo fixation	Unlined pond	Added to sludge in fixation	Closed	OP
Penn Power Co.	Bruce Mansfield No. 2	CL	Pipe	Dravo fixation	Unlined pond	Added to sludge in fixation	Closed	UC
Philadelphia Elec. Co.	Eddystone No. 1A	CL, C	Pipe	N/A	Acid plant	Pond	Closed	OP
Pub. Serv. of Colorado	Valmont No. 5	CL	Pipe	None	Unlined pond	Collected w/SO_2	Closed	OP
Rickenbacker AFB	Rickenbacker	CL	Pipe	None	Lined pond		Closed	OP
S. Carolina Pub. Serv. Aut.	Winyah No. 2	CL	Pipe	None	Lined pond	Disposed in separate pond	Closed	UC
Springfield City Util.	Southwest No. 1	CL, F	Truck	None	Landfill	Mixed w/sludge	Closed	UC
Tenn. Valley Authority	Shawnee No. 10A	CL, F, C	Pipe	None	Unlined pond	Collected w/SO_2	Closed	OP
Tenn. Valley Authority	Shawnee No. 10B	CL, F, C	Pipe	None	Unlined pond	Collected w/SO_2	Closed	OP

[1] CL = Clarifier
F = Vacuum Filtration
C = Centrifuge

[2] OP = Operational
UC = Under Construction, due to go on line by 6/77.

Table 6 (continued)

Power Station		FGD Sludge Disposal						
Utility	Unit	Dewater[1]	Transport	Treatment	Disposal	Fly Ash Disposal	Scrubber Liquor Circulation Loop	Status[2]
Tenn. Valley Authority	Widows Creek No. 8	None	Pipe	None	Unlined pond	Disposed w/sludge in common pond	Closed	UC
Texas Util. Co.	Martin Lake No. 1	CL, C	Railcar	None	Landfill	Mixed w/sludge	Closed	UC
Utah Power & Light Co.	Huntington No. 1	F	Truck	None	Landfill	Mixed w/sludge	Closed	UC

[1] CL = Clarifier
F = Vacuum Filtration
C = Centrifuge

[2] OP = Operational
UC = Under Construction, due to go on line by 6/77.

The following variables were considered as rationale for subcategorization:

1. Size, age of plant, and financial strength;
2. Type of plant or fuel;
    a. power boiler, steam boiler, metallurgical furnace;
    b. coal, coke, oil fuel;
    c. boiler design - tangential, wall fired, grate fired, etc.
3. Type of air pollution control and FGD equipment:
    a. particulate control - electrostatic, venturi scrubbers, mechanical collectors, etc.;
    b. FGD equipment - venturi, packed bed, horizontal spray, mobile bed, tray tower, etc.;
    c. reagent process type - lime, limestone, double alkali, etc.;
    d. operating variables - unsaturated operating mode, scrubber L/G ratio, method and time of reagent addition, etc.
4. Untreated (raw) waste characteristics:
    a. chemical characteristics;
    b. physical characteristics;
5. Disposal site characteristics:
    a. present and future land values and possible uses;
    b. groundwater resources - quantity and quality;
    c. disposal site hydrology and mass transport potential - permeabilities, hydraulic gradients, impurity attenuation, flooding potential, etc.;
    d. disposal site meteorology - evaporation and precipitation rates, etc.;
    e. local ecology;
    f. geographic location;

g. amount of degradation which is acceptable.

The following is a brief analysis of each rationale as it applies to FGD sludge disposal subcategorization.

Size, Age of Plant, and Financial Strength

The use of size, age, or financial strength as variables for subcategorization is not recommended for the following reasons:

- The economics of scale associated with FGD disposal operations are minimal in the range required for utility plants;
- The age of the plant has little effect upon FGD disposal operations. It is probable that few old plants will be equipped with FGD equipment since (1) most will choose to utilize low sulfur fuel, (2) many old plants are used for peaking purposes where the economics of FGD are prohibitive, and (3) the impetus for FGD falls primarily under the New Source Performance Standards.
- The financial strength of the plant is not a logical reason for subcategorization because power utility industry rates are government regulated. FGD disposal costs will be passed on to the consumer, which makes it important that each plant be free to select the most cost effective method of disposal that affords acceptable environmental protection.
- The cost of FGD sludge disposal is significantly less than the cost of the FGD system producing the sludge and does not affect plant location. The FGD sludge disposal cost makes only a small contribution to decisions regarding plant closures or location, installation of FGD equipment, use of low sulfur fuel, etc.

Type of Power Plant and Fuel

Obviously, the type of plant and the fuel used have an influence upon the quantity and characteristics of the FGD sludge produced. However, the interrelationships are very complex among many of the variables (e.g., boiler design, efficiency, excess air used, type of FGD equipment, etc.). The complexity of assessing and defining the quality of a FGD sludge according to coal type and boiler configuration is such that subcategorization from these parameters is infeasible.

Type of Air Pollution Control and FGD Equipment

Subcategorization with respect to FGD and particulate control equipment is not practical. The type and efficiency of particulate control equpment are indeed major determinants of the amount of fly ash available for collection by the desulfurization equipment. The size distribution of the ash being removed with the sulfur oxides has an influence on the chemical composition of the sludge. However, solubility relationships rather than total solid phase concentrations of contaminants in the sludge often control their transport rate from the disposal site. The physical properties of the sludge are partially determined by the details of the scrubber design, which affect nucleation and crystal growth kinetics and sulfite/sulfate ratios (oxidation rates). These interactions are very complex and not fully understood.

Untreated (Raw) Waste Characteristics

FGD sludge waste characteristics may vary widely with time. The chemical properties of FGD sludge also vary with the time and composition of coal fired. Certainty of consistent supply of a specific coal type to a plant for its expected useful lifetime is not always realistic. The range of chemical properties is such that normal variations in coal type could shift the subcategorization of certain FGD system users. This situation is not desirable from the regulatory viewpoint.

The physical properties of the sludge can impact on both the future land use and airborne dust problems. The physical properties desired at any given site will depend upon site-controlling variables and their requirements. Since the physical properties depend upon so many interrelated factors, it does not appear that any single property or combination of properties would be suitable for categorization purposes.

Disposal Site Characteristics

It is recommended that FGD disposal regulations be based upon disposal site characteristics. As discussed in Appendix A, disposal site characteristics include:

- Environmental resources requiring protection;
- Ability of the disposal site to protect these environmental resources, either naturally or through changes made in sludge characteristics and/or site improvements (liners, dikes, etc.); and
- Site monitoring.

Any subcategorization system should satisfy the following criteria:

- The basic variables should be measurable and easily specified.

- They should be the dominant basic variables influencing the controlling considerations.

- The basic variables used for subcategorization should be constant with time.

Disposal site basic variables satisfy the above subcategorization criteria. The disposal site variables are measurable and easily specified. Standard methods exist for determining and reporting permeabilities, hydraulic gradients, evaporation/precipitation rates, etc. The disposal site variables are the ultimate influence upon the control variables. Mass transport rates of contaminants are controlled by disposal site permeability, contaminant attenuation, hydraulic gradients, etc. The degree of reliability required for retaining dams or impoundments is a function of local ecology, geographic location, etc. The disposal site variables are constant with time. For the projected duration of FGD sludge disposal operations at a certain site, the basic disposal site variables are not expected to change appreciably.

The reader is referred to Appendix A where disposal options based upon site characteristics is presented.

SECTION V

SULFUR OXIDE CONTROL TECHNOLOGY

INTRODUCTION

Utilities and other industries burning fossil fuels can select from three general categories of control systems to achieve compliance with standards:

- FGD systems with sludge generation
- FGD systems that produce a marketable product
- Control systems that do not generate a sludge

It is outside the scope of work of this report to discuss in detail the technical and cost factors involved in selecting in-plant sulfur oxide control systems. General considerations include:

- Capital requirements for FGD system construction
- Annual FGD operation and maintenance costs
- Full-scale operating experience
- Land availability
- Types and costs of available fuel
- Available by-product markets
- Energy requirements
- Sustained capability to meet pollution control standards

This section will concentrate upon those aspects of the various in-plant control systems that affect the volume and character of the waste sludge generated.

STATE-OF-THE-ART

As of June 1977, 49 FGC systems will be in commercial operation in the U.S. Of these, 41 will be installed on utility plants and 8 on industrial fossil fuel-fired steam generators. Table 7 differentiates the number and capacity of these operational systems by FGD process. This table shows that the lime/limestone systems account for 34 utility scale systems and for more than 90 percent of the total scrubbing capacity. Double alkali systems currently dominate the industrial scale FGD market, although several of these smaller systems were conceived as pilot or demonstration facilities.

TABLE 7. SUMMARY OF OPERATIONAL FLUE GAS DESULFURIZATION SYSTEMS*

FGD Process	Number in Operation	Total MW Capacity
Utility Scale		
Lime scrubbing		
Lime	12	3,897
Lime/alkaline ash	2	720
Limestone scrubbing		
Limestone†	18	4,267
Limestone/alkaline ash	2	1,390
Wellman-Lord scrubbing	1	115
Dilute acid scrubbing	2	23
Sodium carbonate scrubbing	3	375
Magnesium oxide scrubbing	1	120
Industrial Scale		
Double alkali scrubbing	7	243
Sodium carbonate scrubbing	1	150

* For fossil fuel-fired steam generators as of June 1977.

† At TVA Shawnee's Nos. 10A and 10B power plants (20 MW total), FGD is alternated between lime and limestone scrubbing for experimental purposes. These plants (both the number of them in operation and their megawatt capacity) are included under limestone scrubbing for convenience.

Projections through the year 1985 indicate that lime/limestone systems will continue to dominate the FGD field. However, several large-scale double alkali systems are expected to go on line before 1990.

The majority of plants throughout the utility industry are presently achieving compliance with emission standards through the use of low sulfur fuels. Other plants face compliance schedules calling for the use of either low sulfur fuel or FGD. In addition, at several utility plants, the applicability of sulfur oxide control requirements is embroiled in litigation. It has been estimated that due to the scarcity of low sulfur fuels, 65,000 MW of existing coal-fired generating capacity will need to select FGD systems (Ref. 129). Including high sulfur oil users, this figure is expected to exceed 100,000 MW by 1980. Consequently, the demand for FGD systems will continue to exceed the supply beyond 1985.

FGD SYSTEMS WITH SLUDGE GENERATION

Primarily nonregenerable FGD systems are employed by industries and utilities. Available options for nonregenerable FGD systems are:

- Lime scrubbing (tail end)
- Limestone scrubbing (tail end)
- Double alkali scrubbing (sodium, ammonia)
- Sodium carbonate scrubbing

Lime Scrubbing (Tail End)

The 12 lime scrubbing units presently in operation have accumulated over eight years of intermittent operational experience. The chemistry of the lime scrubbing process proceeds in two stages: (1) the absorption of SO_2 and CO_2 gases by the solution and their subsequent hydration to $SO_3^{=}$, or oxidation to $SO_4^{=}$ and $CO_3^{=}$; and (2) the reaction of these anions with the calcium cation to form calcium sulfite, calcium sulfate, and calcium carbonate precipitates.

The reaction mechanisms associated with each stage are as follows: (Ref. 100)

Stage I

$$CaO + H_2O \rightleftarrows Ca(OH)_2\ (s)$$

$$Ca(OH)_2(s) \rightleftarrows Ca(OH)_2(aq)$$

$$Ca(OH)_2(aq) \rightleftarrows Ca^{++} + 2OH^{-}$$

$SO_2(g) \rightleftarrows SO_2(aq)$

$SO_2(aq) + H_2O \rightleftarrows HSO_3^- + H^+$

$HSO_3^- \rightleftarrows H^+ + SO_3^=$

$SO_3^= + \frac{1}{2}O_2 \rightleftarrows SO_4^=$

$CO_2(g) \rightleftarrows CO_2(aq)$

$CO_2(aq) + H_2O \rightleftarrows H_2CO_3$

$H_2CO_3 \rightleftarrows HCO_3^- + H^+$

$HCO_3^- \rightleftarrows CO_3^= + H^+$

Stage II

$Ca^{++} + SO_3^= + \frac{1}{2}H_2O \rightleftarrows CaSO_3 \cdot \frac{1}{2}H_2O(s)$

$Ca^{++} + SO_4^= + 2\ H_2O \rightleftarrows CaSO_4 \cdot 2H_2O(s)$

$Ca^{++} + CO_3^= \rightleftarrows CaCO_3(s)$

The pH of the lime scrubbing slurry ranges between 7 and 11 depending upon the amount of slurry recirculated. Reaction kinetics favor the formation of the hemihydrated sulfite, as high pH limits sulfite oxidation to sulfate. The use of high sulfur coal further reduces sulfate formation by forcing reduced retention time of slurry in the scrubber circuit and by lowering the oxygen/SO_2 ratio in the flue gas.

Because of the high reactivity of lime with SO_2, the required stoichiometric ratio of CaO/SO_2 is low. Typical ratios are in the range of 1.1 to 1.2, although lower values have been used effectively in certain systems.

Equipment designs that are prevalent with industrial users are the packed-bed and horizontal scrubbers which utilize large surface areas; adjustable or fixed-throat venturis, which utilize high turbulence; and mobile bed contactors; e.g., UOP's Turbulent Contact Absorber (TCA), which have both large surface areas and high turbulence. Lime scrubbers are followed by a filter or impaction device ("Chevron" design) for demisting entrained aerosols.

The major problem encountered with lime scrubbing is scaling within the system. The scale restricts flows in the scrubbing units, and consequently lowers sulfur oxides removal efficiencies. The most prevalent cure for the scaling problem is the use of a subsaturated scrubbing solution. By careful slurry control, scaling can be minimized while maintaining scrubbing efficiencies.

The 12 full-scale lime scrubbing systems have reported operating time availabilities between 43 and 100 percent (Ref. PEDCO Jan-March 77).

Limestone Scrubbing (Tail End)

Flue gas desulfurization using a limestone scrubbing solution has widespread application. There are 18 such full-scale units presently in operation in the United States and several others being used overseas. Over ten years of cumulative operating experience has been logged by American plants. Tail-end limestone scrubbing involves the absorption of dilute sulfur dioxide gas through turbulent contact with a slurry of limestone and reaction products. The wet gas collectors most often incorporated for limestone scrubbing, to date, are the spray tower, the sieve tray, the packed bed, and the mobile bed contactor designs. Figure 3 presents the typical process flow for a limestone scrubbing system.

The chemistry of the limestone process can be summarized in two stages: first, the absorption of the SO_2 gas by the solution and its subsequent hydrolysis to SO_3 = and oxidation to SO_4 =, and second, the reaction of these sulfite ions with the calcium cation to form dihydrated calcium sulfate and hemihydrated calcium sulfite. The reaction mechanisms generally are as follows:

Stage I:

$$SO_2(g) \rightleftarrows SO_2(aq)$$

$$SO_2(aq) + H_2O \; H_2SO_3 \rightleftarrows HSO_3^- \; (aq) + H^+$$

$$HSO_3 \rightleftarrows H^+ + SO_3^=$$

$$SO_3^= + \tfrac{1}{2}O_2 \rightleftarrows SO_4^=$$

$$CaCO_3(s) \rightleftarrows CaCO_3(aq)$$

$$CaW_3(aq) \rightleftarrows Ca^{++} + CO_3^=$$

$$CO_3^= + H^+ \rightarrow HCO_3^-$$

$$HCO_3^- + H^+ \rightarrow H_2O + CO_2 \; (\overset{\uparrow}{g})$$

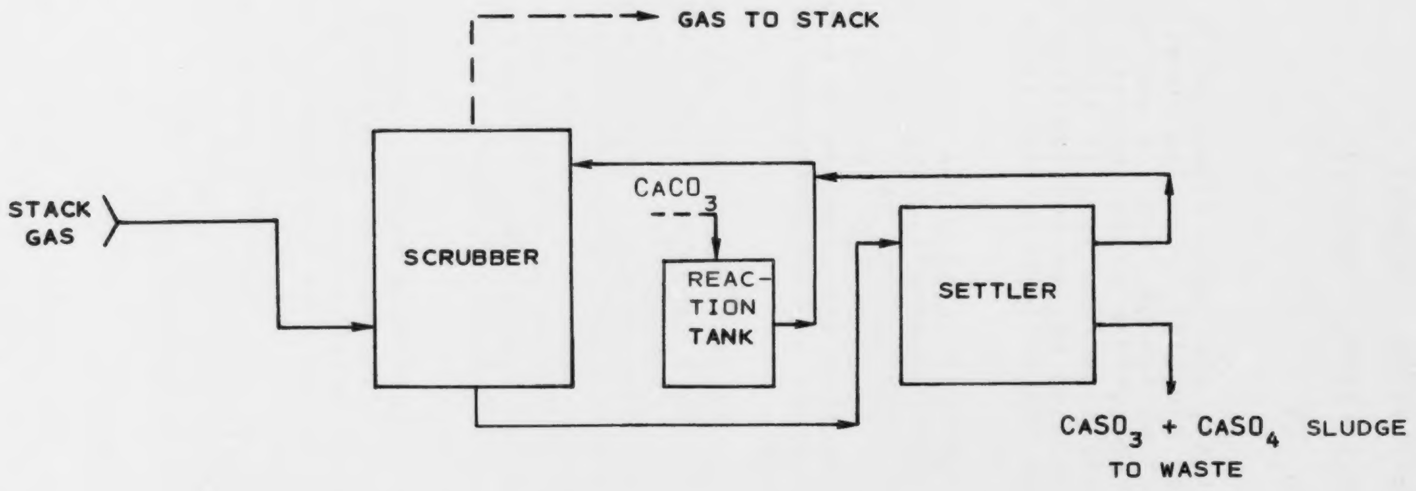
GAS TO STACK
STACK GAS
SCRUBBER
$CACO_3$
REAC- TION TANK
SETTLER
$CASO_3 + CASO_4$ SLUDGE TO WASTE

Figure 3. Scrubber Addition of Limestone

Stage II:

$$Ca^{++} + SO_3 = +\tfrac{1}{2}H_2O \rightleftarrows CaSO_3 \cdot \tfrac{1}{2}H_2O(s)$$

$$Ca^{++} + SO_4 = + 2H_2O \rightleftarrows CaSO_4 \cdot 2H_2O(s)$$

$$Ca^{++} + CO_3^{=} \rightleftarrows CaCO_3(s)$$

In the limestone system, the input liquor pH is approximately 5 to 5.5. Reaction kinetics favor the formation of the dihydrated sulfate complex at low pH, e.g., a decrease in pH from seven to four increases the sulfite oxidation rate up to ten times (Ref. 176). The oxidation rate is also influenced by other system parameters such as oxygen availability and sulfite concentration. This makes the sulfate/sulfite ratio difficult to predict.

The stoichiometric ratio of calcium ion concentration to absorbed sulfur dioxide gas is generally somewhere between 1.3 and 1.5, although some advanced systems have effectively approached a stoichiometric ratio of 1.0. Several pilot plants have demonstrated SO_2 collection efficiencies in excess of 90 percent, while full-scale units are currently operating in the 70-90 percent removal range.

In addition to the gas-liquid contractor, most scrubber systems include a demister and a reheater. Demisters remove entrained aerosols from the scrubbed flue gas and usually consist of an inertial impaction device. Impaction plates are washed periodically to prevent clogging and buildup of solids. At various FGD installations, reheaters are used when atmospheric conditions or operational efficiencies indicate the need to impart buoyance to the cooled exhaust gas. These reheaters consist of either steam-heated tubes or direct fossil fuel heating.

Limestone scrubbing systems have experienced several operational problems in the past, most of which have been rectified through trial and error procedures. Typical problems include solids deposition on the flue gas reheater and demister surfaces, surface metal erosion, and acid corrosion. FGD system availability at a majority of the limestone scrubbing units has been limited due to the startup status of the systems. However, the systems that have been on line for a few years have reported availabilities approaching 95 percent (Ref. 122).

Double Alakli Scrubbing (Sodium)

In the United States, the majority of double alkali systems are installed on industrial boilers. There are currently no operational full-scale utility double alkali systems. However, one is under construction at the 575-MW Central Illinois Public Service Newton No. 1 plant, and two other contracts have been awarded elsewhere. In Japan, there are several oil-fired utility plants using double alkali systems.

To date, research on double alkali scrubbing has concentrated on tail-end scrubbing of the flue gas with a liquor of sodium salts, followed by treatment with hydrated or calcined lime or limestone. Other processes utilizing ammonium or magnesium scrubbing liquor have been investigated, but none has been developed into full-scale systems. Figure 4 displays the process flow for sodium scrubbing with lime regeneration.

The chemistry of the sodium/lime double alkali system can be summarized in two physically distinct stages: (1) a gas absorption and reaction stage, and (2) a precipitation and regeneration stage. The related overall reaction mechanisms proceed as follows:

Stage I (collection)

$$Na_2SO_3 + SO_2 + H_2O \rightleftarrows 2NaHSO_3(\ell)$$

Stage II (regeneration)

$$2NaHSO_3 + Ca(OH)_2 \rightleftarrows Na_2SO_3 + 3/2\ H_2O + CaSO_3 \cdot \tfrac{1}{2}H_2O$$

The clear sodium sulfite liquor is recirculated, while the calcium sulfite is precipitated and drawn off for disposal. A variation of this system is being investigated at the General Motors Chevrolet plant in Parma, Ohio. This variation employs sodium hydroxide as the reactant and hydrated lime as the additive.

Pilot plant SO_2 collection in excess of 99 percent has been achieved. Efficiency can be enhanced by maintaining the liquor pH between six and seven. A pH below six is avoided because of increased SO_2 vapor pressure in the collector. A pH above nine tends to cause scale formation. Various scrubbing devices have been used in pilot plants.

The scrubber effluent treatment stage appears to be the most critical for operational success. The stoichiometric ratio of calcium additive to collected SO_2 is generally kept between 1.0 and 1.1.

Pilot plants operated to date have used settling and filtration to remove solids from the treated liquor. Filter cake washing is done both to recover dissolved sodium salts for

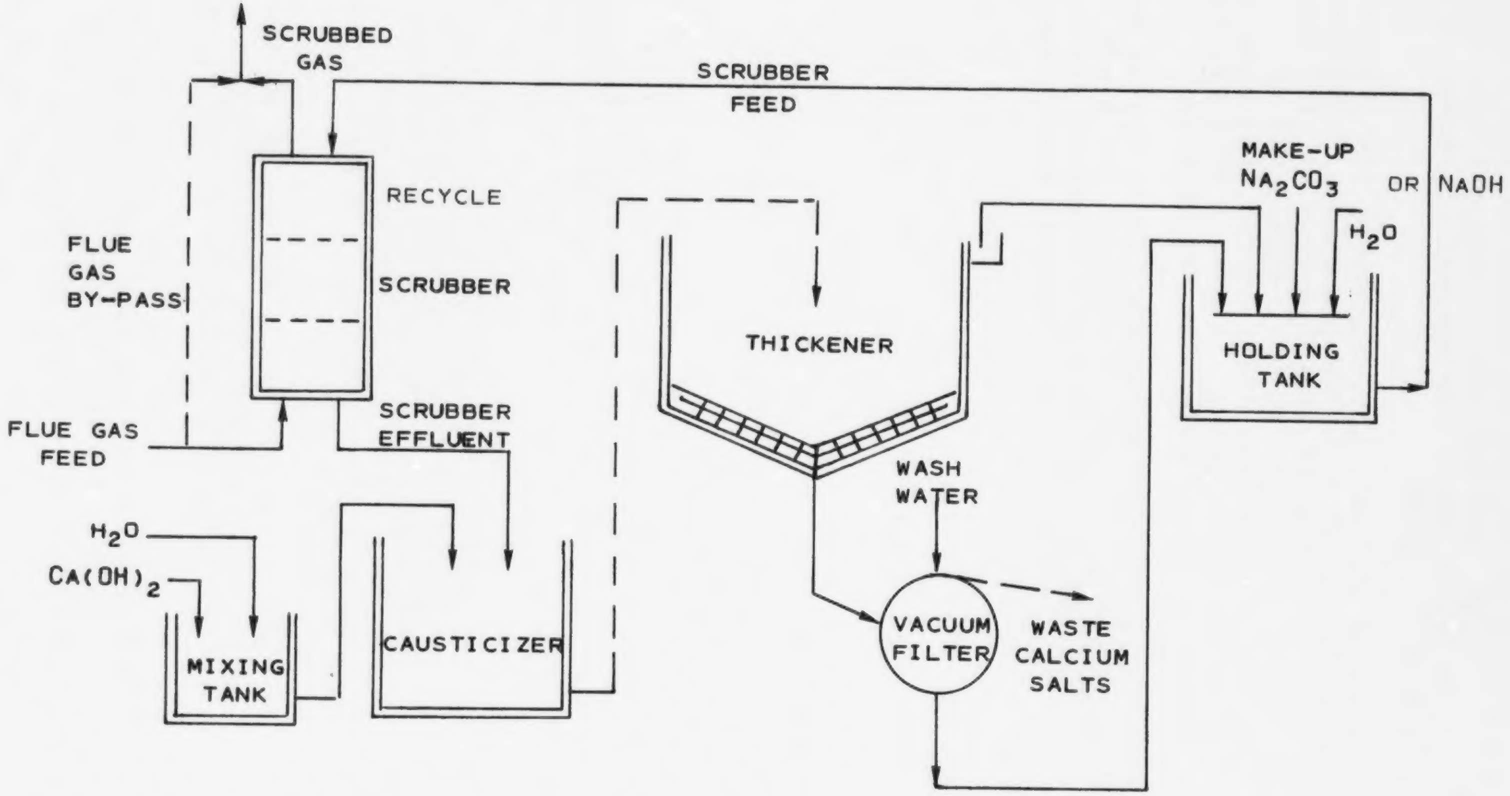
SCRUBBED GAS
SCRUBBER FEED
MAKE-UP
NA_2CO_3 OR NAOH
H_2O
RECYCLE
FLUE GAS BY-PASS
SCRUBBER
THICKENER
HOLDING TANK
SCRUBBER EFFLUENT
FLUE GAS FEED
WASH WATER
H_2O
$CA(OH)_2$
MIXING TANK
CAUSTICIZER
VACUUM FILTER
WASTE CALCIUM SALTS

Figure 4. Double Alkali Process Variation - Sodium Scrubbing with Lime Regeneration (Ref. 28).

recycle to the scrubber and to reduce their concentration in the throwaway sludge (Ref. 163).

The major reported problem associated with double alkali scrubbing has been the loss of sodium salts to the filter cake. The loss of some soluble sodium salts with the sludge is unavoidable, but the loss can be limited by washing the filter cake.

Sodium Carbonate Scrubbing

Sodium carbonate FGD scrubbing is currently employed on three 125-MW utility boilers at the Nevada Power Company Reid Gardner Station, as well as on one industrial boiler. This process, due to the soluble salts concentrations in scrubber liquors, is most practicable in areas where high TDS liquors can be disposed with little environmental hazard. Currently, the process has found application in areas of low humidity or areas with a high evaporation/precipitation ratio.

The system chemistry is based on the following reactions:

$$Na_2CO_3 + SO_2 \rightleftarrows Na_2SO_3 + CO_2$$

$$Na_2SO_3 + SO_2 + H_2O \rightleftarrows 2NaHSO_3$$

Under proper pH conditions, the first reaction predominates so that there is little $NaHSO_3$ in the scrubber effluent. The second reaction is limited if a pH of 5 to 7 is maintained. It has been reported that 0.8 to 0.9 mole of Na_2CO_3 is required per mole of SO_2 removed (Ref. 71).

BY-PRODUCT RECOVERY SYSTEMS THAT PRODUCE A MARKETABLE PRODUCT

There are three factors affecting the feasibility of generating marketable by-products from FGD systems. These are:

- Technology availability
- Consumer/institutional acceptance of the by-product
- Economics and markets

Regenerable FGD technology producing elemental sulfur or sulfuric acid has a proven commercial market in certain areas. Marketing and utilization of FGD sludges or gypsum is currently under investigation by the EPA and other public and private organizations.

FGD by-products must meet with customer approval in order to gain market acceptance. Since these by-products result from pollution control, regulatory and consumer institutions may require proof that the product is safe to both human health and the environment. Institutional constraints also relate to market specifications and governmental rules and regulations. These parameters must be considered for successful utilization of FGD by-products.

Another important consideration for successful by-product utilization is competition in the marketplace. Economic viability is determined by the relative costs of secondary and virgin materials. As virgin materials become increasingly scarce and therefore more expensive, the value of related secondary materials increases. The virgin materials competing with FGD by-products are currently in plentiful supply, but regional shortages and demand growth may render by-product utilization economically attractive in some areas of the country. Utilities are in business to market power. Most utilities balk at the idea of developing sellable FGD by-products in an uncertain marketplace.

Regenerable flue gas cleaning systems have found acceptance for cleaning process gases from heavy industry, e.g., petroleum refineries, sulfur acid plants and non-ferrous smelters. In most cases, the by-product can be added to existing products within the plant without additional marketing efforts. Regenerable systems have been installed on a few power plants with some degree of success.

Regenerable processes may eventually become the predominant scheme for sulfur oxide control. These processes can yield gypsum elemental sulfur and sulfuric acid, all of which have proven market value.

The current market for nonregenerable FGD sludge is very limited, and disposal is generally more cost effective than recovery. Potential markets for FGD sludge include use as gypsum, structural landfill, synthetic aggregate, mine void backfill, soil amendment, and acid mine drainage control or treatment. Research has shown these alternatives to be technically feasible under proper conditions of treatment and control.

FGD by-product recovery can therefore be classified as either (1) regenerable FGD with recovery of gypsum or sulfur values or (2) use of FGD throwaway sludge. The following subsections discuss these alternatives.

REGENERABLE FGD SYSTEMS

Regenerable FGD systems can have as their by-products gypsum, hydrogen sulfide, sulfur dioxide, sulfur and sulfuric acid.

Hydrogen sulfide and sulfur dioxide are gases with relatively little commercial value, while gypsum, elemental sulfur, and sulfuric acid are readily marketable. Certain FGD systems that remove and concentrate sulfur dioxide can either oxidize to sulfuric acid or reduce to elemental sulfur. Other systems directly produce sulfur or sulfuric acid. Currently, the most popular systems are:

- Dilute and scrubbing
- Wellman-Lord scrubbing
- Magnesium oxide scrubbing
- Citrate scrubbing

Dilute Acid Scrubbing

The only commercially demonstrated dilute acid scrubbing system is the Chiyoda "Thoroughbred 101" process, which uses dilute sulfuric acid as the absorbent liquid. Oxidation of H_2SO_3 to H_2SO_4 is accomplished by using a soluble $Fe_2(SO_4)_3$ catalyst. A portion of the resulting H_2SO_4 is reacted with limestone to form gypsum. The remainder of the H_2SO_4 is recycled to the absorber. This process is composed of five operations: (1) prescrubbing, (2) absorption, (3) oxidation, (4) crystallization, and (5) by-product handling/disposal.

Figure 5 illustrates the basic process flows for the Chiyoda process. The prescrubber cools the incoming flue gas to its saturation temperature and removes entrained fly ash and chlorides. Sulfur dioxide is then removed in a countercurrent scrubber (fixed bed absorber) using a weak sulfuric acid solution. The absorption yields sulfurous acid, which is air oxidized to sulfuric acid in the oxidizer using a ferric ion catalyst. The solution is then passed to the crystallizer and reacted with limestone to form gypsum crystals. Clarified liquor is then recycled to the absorber.

The Chiyoda process was originally designed for oil-fired systems. There are 13 such systems currently in operation in Japan. A 23-MW demonstration plant started treating flue gas February 1975, at the coal-fired Gulf Power Company Scholz plant near Sneads, Florida. The demonstration program was completed on March 22, 1977. Chiyoda and Gulf Power are currently preparing a comprehensive report on the program. Coal utilized at the Scholz plant has a 3 percent sulfur content; SO_2 removal efficiencies in excess of 80 percent have been obtained. The plant did not operate in the closed-loop mode. Spent acid liquor discharges from the prescrubber average approximately 20 gpm. The liquor is neutralized with limestone and piped to a lined settling pond where fly ash, gypsum, unreacted limestone, and $Fe(OH)_3$ are removed by sedimentation. Concentrations of total dissolved solids, iron, mercury, and fluoride in the supernatant liquor currently exceed state water quality standards for a surface receiving water. This liquor was routed to the Scholz plant ash pond, which ultimately discharges into nearby surface waters.

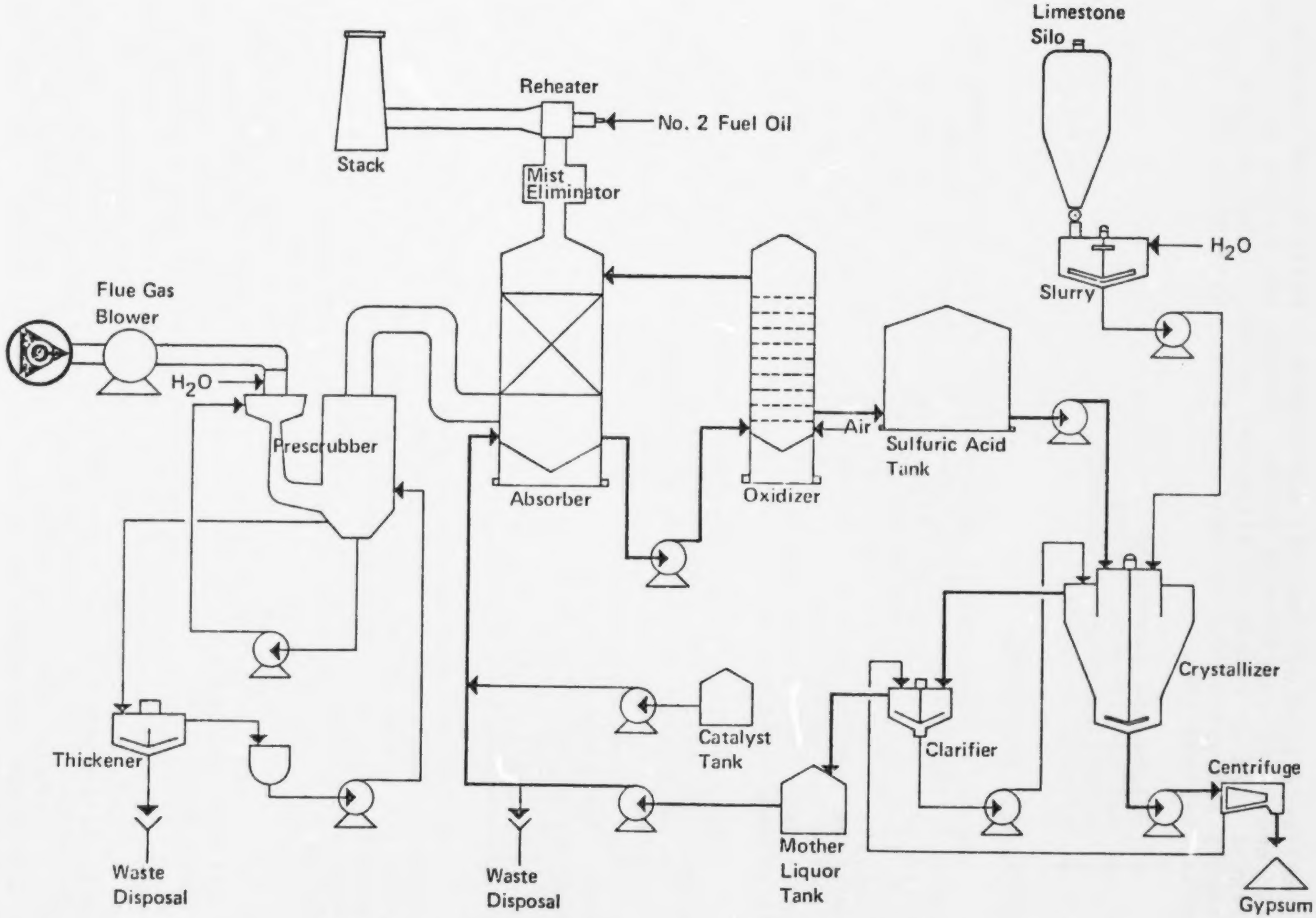
Limestone
Silo
Reheater
No. 2 Fuel Oil
Stack
Mist
Eliminator
H_2O
Slurry
Flue Gas
Blower
H_2O
Prescrubber
Absorber
Air
Sulfuric Acid
Tank
Oxidizer
Crystallizer
Catalyst
Tank
Thickener
Clarifier
Centrifuge
Waste
Disposal
Waste
Disposal
Mother
Liquor
Tank
Gypsum

Figure 5. Chiyoda Thoroughbred 101 Flow Diagram (Ref. 30).

Dewatering of the Scholz sludge by centrifugation has produced an 80 to 85 percent solids filter cake. The gypsum was being disposed of in a lined pond equipped with underdrainage. Permeability of the filtered sludge has been calculated at between 10^{-5} to 10^{-6} cm/sec. Rain water percolated through the gypsum is routed from the underdrain to the ash pond.

Various minor problems limited the unit's availability during the first few months of operation. These problems included (1) maintaining chloride concentrations in the absorption/crystallization section below 200 ppm to prevent corrosion in the stainless steel vessels; and (2) obtaining particulate collection ahead of the absorber to reduce dust and fly ash contamination of the mother liquid and gypsum. However, from October 17, 1976, through program completion, the process utilization was greater than 99 percent.

Wellman-Lord Scrubbing

This process, patented by Davy Powergas, Inc., is a proven method of flue gas desulfurization designed for ultimate recovery of SO_2. The many such systems presently on line in Japan are reported to have a low percentage of downtime and high collection efficiencies. Recently, the Wellman-Lord system was applied to a coal-fired boiler unit at the D. H. Mitchell Station of the Northern Indiana Public Service Company.

Figure 6 shows the typical process flow diagram for this system. The principle of the Wellman-Lord process involves scrubbing the flue gas with a sodium sulfite solution. The bisulfite by-product is then heated, which regenerates the sulfite and produces SO_2 for further processing to sulfuric acid or elemental sulfur. The reaction mechanisms involved in the scrubbing and regenerative steps are as follows (Ref. 164):

Stage I (scrubbing)

$$Na_2SO_3 + SO_2 + H_2O \rightleftarrows 2NaHSO_3$$

Stage II (regeneration)

$$2NaHSO_3 \rightleftarrows Na_2SO_3(s) + SO_2(g) + H_2O$$

Following regeneration, the SO_2 is transported to a sulfur production unit where the concentrated SO_2 is reduced to elemental sulfur using methane gas. It is also possible to convert to liquid SO_2 or sulfuric acid from the recovered SO_2.

There has been little experience with coal-fired units using the Wellman-Lord process; however, several major

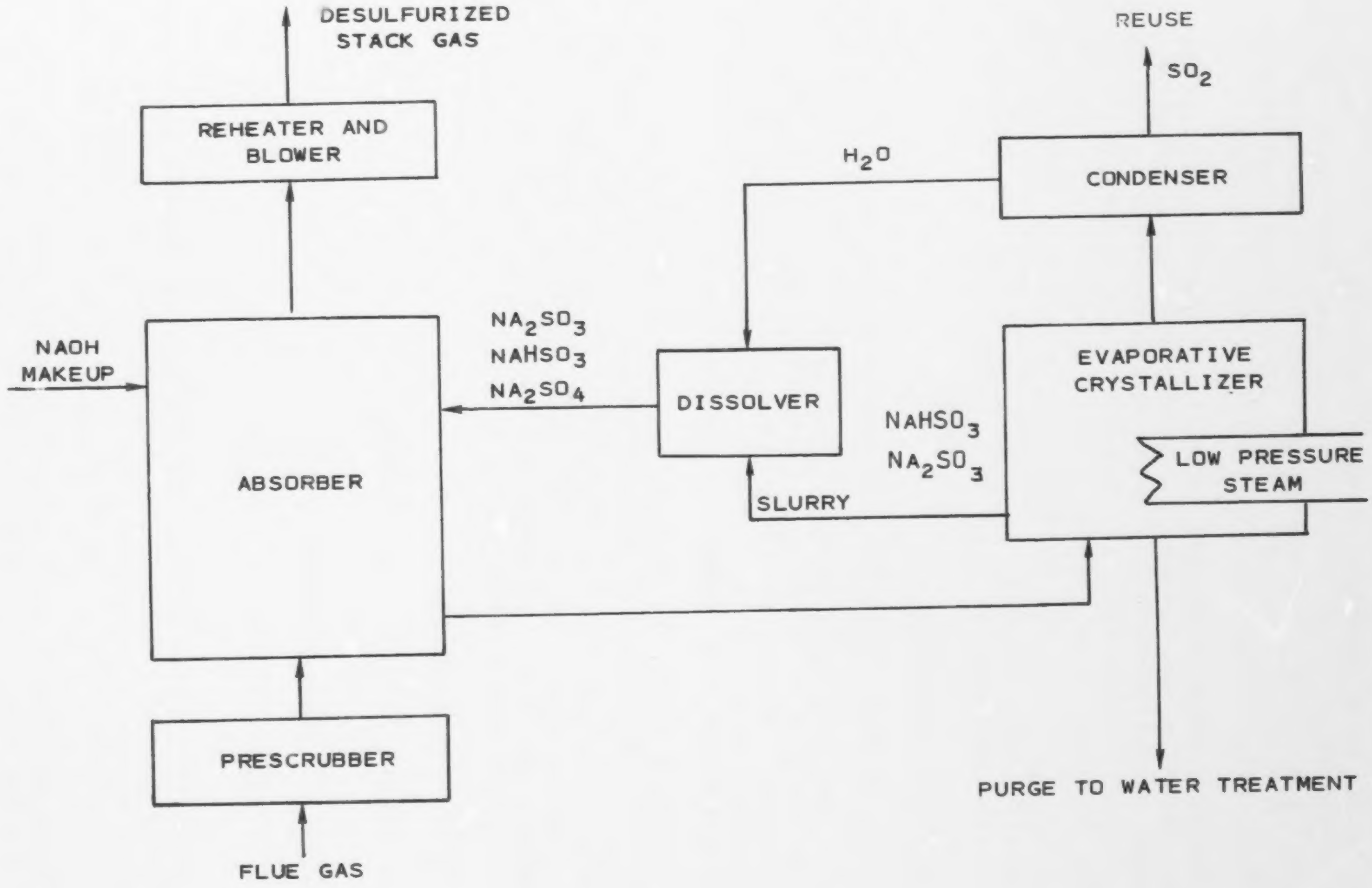
DESULFURIZED STACK GAS
REHEATER AND BLOWER
NAOH MAKEUP
ABSORBER
PRESCRUBBER
FLUE GAS
NA_2SO_3
$NAHSO_3$
NA_2SO_4
DISSOLVER
H_2O
SLURRY
$NAHSO_3$
NA_2SO_3
REUSE
SO_2
CONDENSER
EVAPORATIVE CRYSTALLIZER
LOW PRESSURE STEAM
PURGE TO WATER TREATMENT

Figure 6. Wellman-Lord Process Schematic (Ref. 163)

operational difficulties have been encountered with oil-fired units. One problem is the generation of large quantities of purge solids - particularly sodium sulfate - which are difficult to dispose of properly. Sulfate formation is undesirable as it wastes valuable sodium feedstock. The formation mechanisms are primarily SO_3 absorption, sulfite oxidation, and disproportionation (Ref. 163). Inhibiting additives and initiating process modifications have been successful in preventing oxidation, and low pH oxidation has been used to reduce effluent oxygen demand. This treatment, however, has done little to reduce TDS in the purge discharge.

A second problem with the Wellman-Lord process involves the high steam demand for the dissociation of sodium bisulfite to regain the SO_2 gas. Power plants applying this process to SO_2 control can expect a derating of between three and six percent of rated generating capacity (Ref. 163).

The use of methane in the production of sulfur is a drawback because of the natural gas scarcity. Vendors whose reducing systems rely on methane availability have been researching alternate methods of converting SO_2.

Most of the operational Wellman-Lord scrubbing units have maintained SO_2 collection efficiencies of around 90 percent. Operating time availability has been high in most cases, attributable to the simplicity of the process. All existing units use an absorption tower and employ either sieve plates or packed beds (saddles) as the contactor.

Magnesium Oxide Scrubbing

Magnesium oxide scrubbing is designed as a closed-loop operation, regenerating the magnesia used in the slurry and collecting SO_2 for conversion of sulfuric acid or elemental sulfur. Three such systems have been installed to date. Two plants - PEPCo Dickerson No. 3 and Boston Edison Mystic No. 6 - were shut down when the acid plant regeneration site was forced to discontinue operations. The third plant, Philadelphia Electric's Eddystone No. 1A, has been temporarily shut down while its acid regeneration system is being relocated. In no case have technical difficulties been the major reason for process conversion or shutdown.

A typical flow diagram of this process is shown in Figure 7. In magnesium oxide scrubbing, an aqueous solution of MgO, magnesium sulfite, and magnesium sulfate contacts the flue gas in a venturi absorber unit, collecting the SO_2 and forming several magnesium-sulfur compounds. The scrubber effluent is dewatered to retain the solids and then recirculated. The dry sludge cake, composed primarily of hydrated magnesium sulfite, is transported to a processing facility. There it is thermally

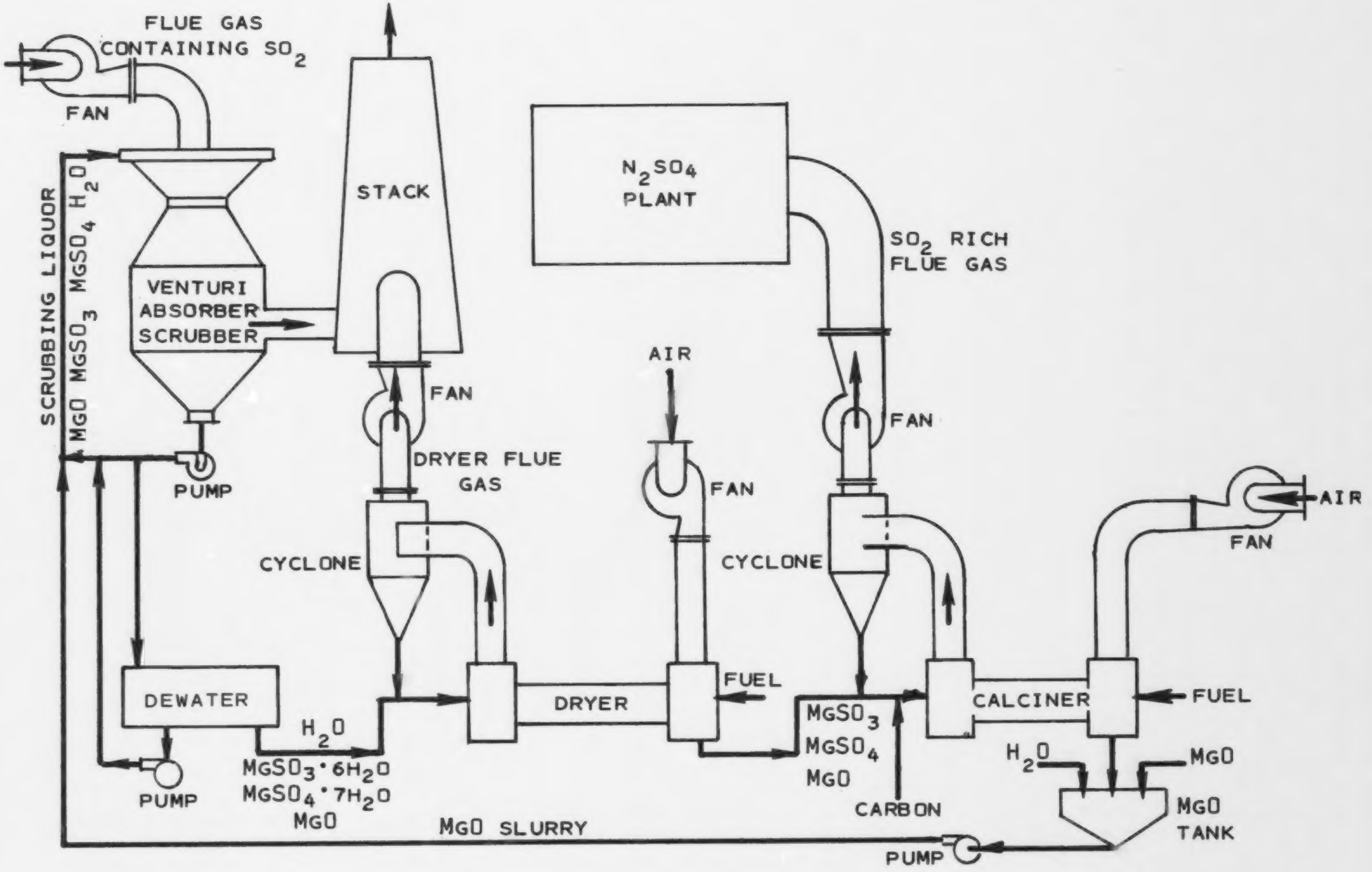
FLUE GAS CONTAINING SO_2
FAN
STACK
N_2SO_4 PLANT
SO_2 RICH FLUE GAS
SCRUBBING LIQUOR
MgO $MgSO_3$ $MgSO_4$ H_2O
VENTURI ABSORBER SCRUBBER
FAN
AIR
FAN
PUMP
DRYER FLUE GAS
FAN
FAN
AIR
CYCLONE
CYCLONE
FAN
DEWATER
FUEL
DRYER
$MgSO_3$ $MgSO_4$ MgO
CALCINER
FUEL
H_2O
H_2O
MgO
$MgSO_3 \cdot 6H_2O$
$MgSO_4 \cdot 7H_2O$
MgO
PUMP
CARBON
MgO TANK
MgO SLURRY
PUMP

Figure 7. MgO Slurry Process - for Flue Gas Free of Particulate Matter (Ref. 11)

dehydrated and calcined for reuse in the slurry. The SO_2 gas is processed into salable by-products.

The majority of operating experience with magnesium oxide scrubbing was acquired at the Boston Edison Mystic oil-fired unit and PEPCo's coal-fired Dickerson station. Problems encountered at the Mystic plant included high percentages of unbound moisture in the filter cake, subsequent occlusion in the dryer drum, inactivity of the recycled magnesium oxide when slurried, and dust control during the drying step. Problems at Dickerson can be traced to off-specification construction materials and extended boiler shutdowns. There was no continuous slurry bleed at any of the power plants.

Citrate Scrubbing

The Citrate Process, pioneered by the U.S. Bureau of Mines (USBM), is designed for the regeneration of elemental sulfur. Pilot plant operations have been constructed by both the Bureau of Mines and Peabody Engineering Systems. To date, no full-scale plants have been installed. However, a joint effort between the USBM and the EPA has initiated construction of a 53-MW demonstration system at St. Joseph Minerals in Pittsburgh, Pennsylvania.

Figure 8 is a schematic diagram of the Citrate Process (Ref. 166). This process proceeds in six steps: (1) cleaning the gas of particles and subsequently cooling the gas below 50°C; (2) scrubbing with a solution of citric acid and sodium carbonate ($pH = 3.8\text{-}4.5$); (3) precipitating the elemental sulfur by bubbling H_2S through the spent liquor; (4) dewatering the sulfur by centrifuging; (5) melting the sulfur via an autoclave; and (6) regenerating the H_2S.

Aside from the obvious advantage of regeneration, the Citrate Process is somewhat unique in its buffering capability. A solution buffered with citric acid shows superior SO_2 solubility compared to other potential agents, thereby reducing the liquid/gas ratio necessary for a given efficiency. The optimal pH values for the Bureau of Mines and Peabody (Citrex) processes are 3.8 and 4.5, respectively; a higher pH would likely increase solubility of SO_2, but increased formation of in-situ thiosulfates would reduce the recovery efficiency by increasing input H_2S and acid requirements (Ref. 163).

Although the two processes claim to produce minimal oxidation of SO_2, this is known to be a problem under certain operating conditions. The oxidated product can be removed from the scrubber loop through the use of additives (such as $SrCO_3$), but the sulfate salt generated is difficult to dispose of properly and results in additional expenditures for feedstock.

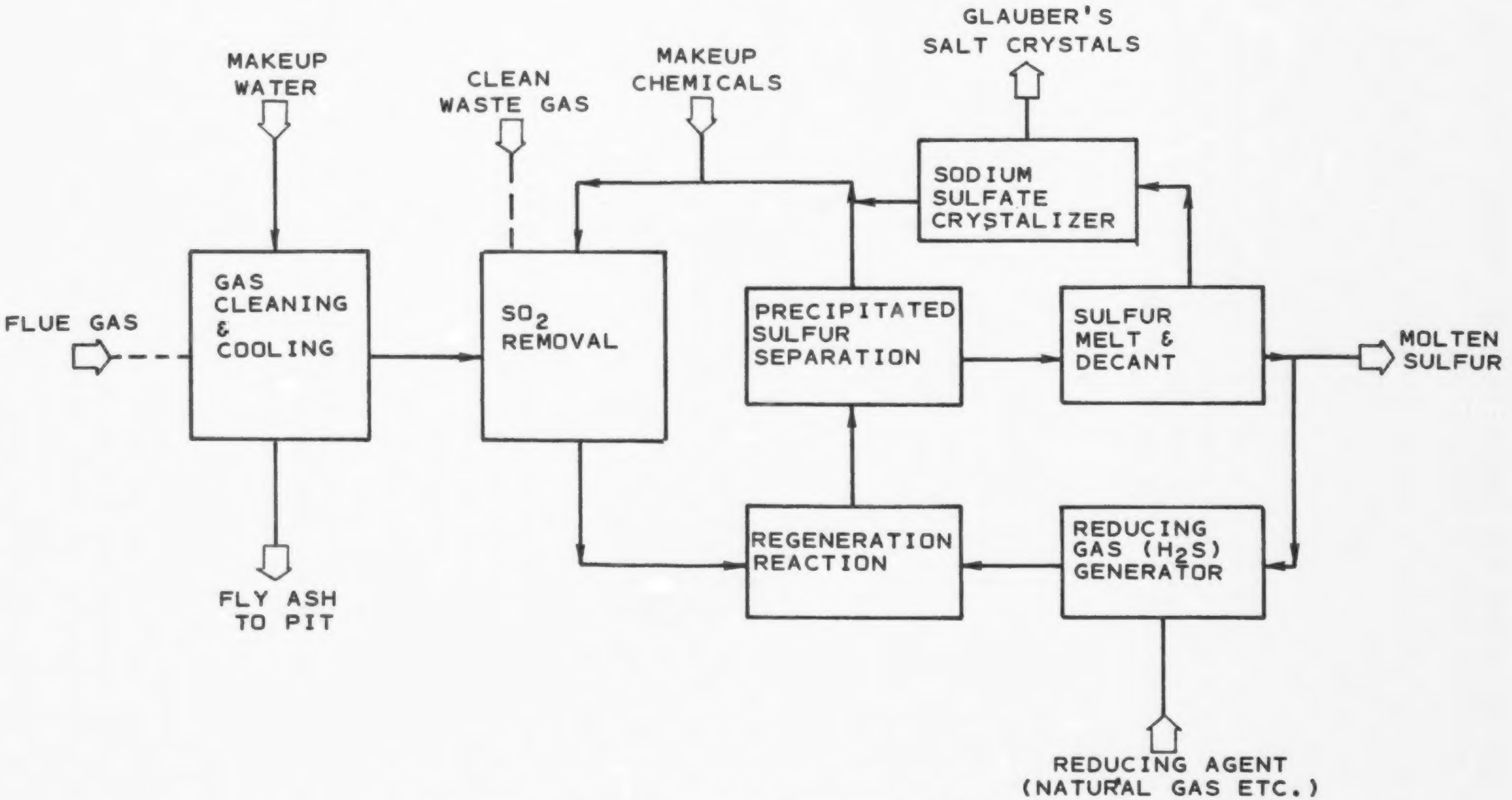
GLAUBER'S SALT CRYSTALS
MAKEUP WATER
CLEAN WASTE GAS
MAKEUP CHEMICALS
SODIUM SULFATE CRYSTALIZER
FLUE GAS
GAS CLEANING & COOLING
SO_2 REMOVAL
PRECIPITATED SULFUR SEPARATION
SULFUR MELT & DECANT
MOLTEN SULFUR
REGENERATION REACTION
REDUCING GAS (H_2S) GENERATOR
FLY ASH TO PIT
REDUCING AGENT (NATURAL GAS ETC.)

Figure 8. Citrate Process (Ref. 166)

Pilot units in operation have been using either sieve-plate or packed-bed tower absorbers for the scrubbing process. Removal efficiencies in excess of 95 percent have been achieved with an L/G ratio of less than ten. By-product sulfur purities of 99 percent or above are common. Citrate losses are attributed to spills or oxidation. Peabody reports losses from pilot plant studies of 6 to 7 lb/ton of sulfur recovered.

The future of citrate scrubbing is unclear. Although pilot studies have indicated that the process may be less costly than other methods, scale-up of certain system components may be difficult, thus reducing its cost effectiveness. Consideration of oxidation kinetics and cost factors indicates that citrate scrubbing will be used primarily to treat flue gases with high concentrations of SO_2.

Lime/Limestone Sludge Utilization

In order to avoid the problems associated with FGD sludge disposal, research has been in progress in the area of nonregenerable sludge utilization. Technical developments for FGD sludge reuse have largely followed precedents established for the utilization of fly ash. Table 8 lists both present and proposed uses for FGD sludge. Current and past sludge utilization investigations include:

- Autoclaved products, brick, and aerated or foamed concrete and concrete materials, by the Coal Research Bureau of West Virginia University;
- Use as an aggregate in highway construction by the Gillette Company Research Institute.

Under EPA sponsorship:

- Elemental sulfur and calcium carbonate recovery, by the Pullman Kellogg Co.;
- Use as a filler material and source of sulfur in fertilizer, by TVA;
- Use of FGC gypsum in Portland cement manufacturing, by Santee Portland Cement Corp. and South Carolina Public Service Authority;
- Recovery of minerals, sulfur, alumina, and dicalcium silicate, by TRW.

Presently, the most feasible utilization schemes appear to include sludge conversion to gypsum, for use as a building material, structural landfill, synthetic aggregate, mine void backfill, soil amendment, and control of acid mine drainage.

TABLE 8. SLUDGE UTILIZATION SCHEMES*

Construction Materials

- Pavement
- Pavement base
- Cement manufacture
- Concrete admixture
- Mineral aggregate
- Sinter bricks
- Autoclaved bricks
- Autoclaved concrete blocks (poured and aerated)
- Plaster
- Wallboard
- Mineral wool
- Lightweight aggregate

Environmental Uses

- Structural fill for land recovery
- Structural fill for sanitary landfill
- Structural fill for mine subsidence control
- Fill for fire control in abandoned mines
- Neutralization or prevention of acid mine drainage
- Reclamation of polluted lakes
- Filter aid for sewage sludge dewatering
- Tertiary treatment of sewage
- Soil amendment
- Soil stabilization

Mineral Recovery

- Sulfur
- Aluminum
- Lime or limestone
- Magnesium oxide
- Iron
- Titanium
- Silicon
- Rare earths

Fillers for Manufactured Products

- Glass
- Fertilizer
- Paint
- Plastic
- Rubber

Miscellaneous

- Ceramic materials
- Sand blasting grit
- Porous pipe
- Metal coatings
- Grouting agent for wells

* Ref. 13

The technologies for these utilization schemes are already developed. Although these products are in many ways equal to existing materials, utilization has been limited because (Ref. 129):

- Sludge is produced in a wet state and must be thoroughly dewatered for many uses;
- Sludge properties can be highly variable, creating potential quality control difficulties;
- Sludge use in sintered products manufacture causes the release of sulfur dioxides;
- The contaminant content (e.g., salts and heavy metals) of sludge presents a potential problem of water pollution for certain applications, such as soil amendment and acid mine-drainage neutralization;
- Severe competition exists from current virgin material supplies;
- General apathy of industry to the utilization of secondary materials;
- High capital investments are necessary to produce autoclave products, e.g., bricks or blocks; and
- Technology for mineral recovery is undeveloped or very costly.

Gypsum--

Gypsum produced from scrubber waste would have to compete with a sautrated virgin gypsum market in the United States. Japan is the only country in which gypsum is produced from FGD and marketed primarily for wallboard and portland cement. Japan's scrubber systems are in many cases equipped with sulfite oxidizing units, which produce gypsum containing as little as 10 percent moisture. The high cost of oxidation has until recently been offset by gypsum's high market value in Japan. Since 1975, however, gypsum supply has exceeded demand and has forced many power plants to store the excess in place of disposal.

The purity and consistency in composition of gypsum produced from FGD sludge is expected to be met with skepticism in the United States. However, Chiyoda gypsum from the Gulf Power Company's Scholz plant was tested and judged suitable for wallboard manufacture (Ref. 131).

Agricultural utilization of FGD gypsum is a possibility for the amelioration of natric or solonetzic soils (Ref. 149). The gypsum could act as a calcium source for plants or calcium deficient soils. Chiyoda gypsum is under investigation by the University of Florida Agricultural Research Center for use on peanuts and soybeans (Ref. 133). It has also been noted (Ref. 141) that FGD gypsum combined with fly ash has the ability to improve the texture and drainage characteristics of some soils. Another potential advantage is that the FGD gypsum slurry may be sprayed directly on the soil iwthout the need for prior drying.

Fertilizer Production--

The use of lime and limestone scrubber wastes as a filler material and source of sulfur in granular fertilizers is being evaluated by the Tennessee Valley Authority. Qualitative field tests on rye grass have shown no apparent detrimental effects from the addition of FGD sludge-based fertilizer. Quantitative field tests have not been completed to assess either trace metal or toxic material effects and/or concentration in the plants, along with their rates of leaching.

There have been both physical and chemical problems with fertilizer manufacture. Physical difficulties have been caused by excess moisture in the sludge adversely affecting granulation. The fertilizer has also shown a high propensity for rewatering. A major chemical problem has occurred in the preneutralizer, in which low pH (from phosphoric acid addition) causes high solubilization of calcium sulfite and consequential loss of sulfur dioxide to the atmosphere.

Sulfur losses ranged from 78 to 90 percent by weight of the total sulfur added, while ammonia losses ranged between 34 and 61 percent by weight of the ammonia added (Ref. 133).

A procedure has been proposed for elimination of these unwanted reactions. This procedure would promote either the oxidation of calcium sulfite to calcium sulfate before feeding to the preneutralizer or neutralization of the phosphoric acid before it comes into contact with the sludge. Testing of these procedures has not yet been completed at TVA (Ref. 130).

Aggregate in Construction--

Laboratory investigations were reported in 1975 by the Gillette Company Research Institute to evaluate the performance of FGD sludge use in construction (Ref. 149). Various mixtures of water with lime, fly ash, and sludge were tested for use as filler material in road building operations and as aggregate particles in Portland cement and asphaltic concrete mixtures. From the results of engineering tests, the following conclusions were made:

- When properly proportioned, compacted, and cured, the sludge mixtures produced a strong, stiff material that may be suitable for use in embankments, subgrades, and subbases and bases for pavements.
- The durability of these mixtures when tested by freeze-thaw and wet-dry tests was insufficient after seven days of 23°C curing. Durability was still insufficient, but had improved after a 28-day 23°C, curing period. The study suggests that the use of lime-fly ash-sludge mixtures for pavement components in cold climates should be considered with caution.
- Selected mixtures were relatively impervious and might be employed in dikes, lagoons, and levees.
- Compacted lime-fly ash-sludge mixtures were normally lighter in weight than compacted soils. This feature would be advantageous where soft, compressible ground is to be crossed by an embankment.
- Initial effluent leachate concentrations of TDS were high as soluble lime and gypsum materials were leached. Leachate TDS concentrations showed approximately a 75 percent decrease after a 28-day period.

The use of lime-fly ash-sulfate mixture as an aggregate for Portland cement and asphaltic concrete was evaluated. The major conclusions were:

- Tests of concrete mixtures indicated acceptable strength values for specialized applications, but unacceptable durability factors for prolonged exposure to cyclic freezing and thawing environments. These results suggest that concrete mixtures may perform satisfactorily in warm climates not subject to freezing and thawing.
- Admixtures normally used to enhance pozzolanic reactions were found to have little effect on strength development.
- Aggregate used in concrete and cement mixtures had high absorption characteristics and did not pass either standard soundness tests or the Los Angeles abrasion test.
- Apparent leaching of the aggregates occurred during the freeze-thaw testing, depositing an unidentified white material in the regions of surface cracks.

In summary Gillette recommended that curing time be increased to between six and nine months and that adequate protection from freezing and thawing be provided; this would afford a stronger, more resistant aggregate particle capable of selected construction applications.

OTHER NON-SCRUBBING DESULFURIZATION OPTIONS

The high cost of wet scrubbing techniques has prompted many public and private institutions to seek alternate means for reducing SO_2 emissions. Some of these techniques are:

- Fuel switching from high sulfur coal to natural gas, oil, or low sulfur coal
- Coal cleaning
- Fluidized bed combustion
- Coal gasification

Many of the techniques are still in the developmental stages, but accelerated research may in a few years promote them to commercially available status. Alkalized alumina, activated carbon, and catalytic oxidation were discussed in previous subsections.

Low Sulfur Fuel

A reduction in sulfur dioxide emissions can be accomplished by switching to a low sulfur fuel, i.e., a fuel low enough in sulfur content to meet federal or state emission standards. The use of low sulfur coal to meet emission standards is technologically simple, but may be difficult to justify economically. A coal switch requires only a moderate capital investment (for particulate collection and plant conversions), but power plants that were originally designed to burn one type of coal may experience operational difficulties in burning another type. For example, the replacement of high sulfur western coal with western lignite and subbituminous coals - which are low-Btu, low sulfur, high ash varieties - may double the ash disposal requirements while also derating the boiler. The use of eastern low sulfur coal does not present these problems, but supply-demand pressures have forced the price up substantially. The capital cost of a coal switch has been estimated at between $5 to $15/KW (Ref. 129).

Use of a low sulfur distillate oil as the primary fuel is common among plants that were originally equipped to use oil as a standby fuel. The major drawback to its use is price. Fuel oil prices have increased rapidly since 1974, and the installation of large oil storage capacities is difficult to justify under such unstable market conditions. A switch to oil firing is a valid interim solution to the SO_2 emission problem, but future cost uncertainties make long-range planning difficult for management. Recent statements by the Federal Energy Administration (FEA) and the Administration have stressed decreasing dependence on imported oil and development of United States coal reserves.

In order to comply with ambient SO_2 regulations, several eastern power plants employ low sulfur fuels only when meteorological conditions might hinder pollutant dispersion. Intermittent controls are a highly sophisticated art, employing complex predictive modeling of atmospheric dispersion to determine when and to what degree boiler operation should be modified. Typical of intermittent control systems are the "Sulfur Dioxide Emission Limitation" (SDEL) by TVA and "Dynamic Emission Controls" (DEC) by the Department of Commerce; neither is endorsed by EPA except as an interim control measure. The major criticism of intermittent controls is that they do little to reduce total SO_x and heavy metals loading to the biosphere over the long range.

Tall Stacks

Stacks as high as 1,000 ft have been constructed to direct power plant exhaust away from the local environment. The gases are released so high that they are sufficiently dispersed in any weather conditions, thereby meeting ambient standards. Like intermittent controls, the relationship between stack height and meteorological conditions has been studied in detail and is used to determine the proper height for specific site conditions.

Although regulatory agencies consider tall stacks only an interim solution to the SO_2 problem, power plants continue to build them. Even if additional air pollution control equipment is installed, it is considered desirable to have the dispersion capability in case of control system failure.

Coal Cleaning

In 1977, 40 to 60 percent of the coal mined in the U.S. will be cleaned of impurities for use in steelmaking operations. The conventional cleaning systems are designed to remove mineral matter, not to remove sulfur. During recent years, however, substantial research has been directed toward developing techniques for removing sulfur from coal.

There are several obstacles to desulfurization of coal, which generally relate to the type of sulfur and how it is situated in the coal matrix. Inorganic pyritic sulfur, contained as FeS_2, is a physically distinct portion of the coal and can be removed by physical means. Organic sulfur is bound to the various hydrocarbons in the coal matrix, and this sulfur cannot be physically separated.

Physical separation techniques include screening, froth flotation, air classification, magnetic separation, and dense media separation. These techniques utilize the difference in physical properties between coal and pyrite.

Where pyritic sulfur comprises a majority of the sulfur present, physical separation alone is often sufficient to reduce total sulfur to acceptable levels. However, it is estimated that only 16 to 17 percent of all coal mined in the U.S. can be sufficiently cleaned of sulfur by physical means to meet air standards when burned.

Chemical removal is being investigated with some success. TRW has developed a process for leaching the sulfur with ferric sulfate. The resulting solution of ferric sulfate, sulfuric acid, and sulfur is volatilized to remove the elemental sulfur and regenerate the original solution. Ledgemont Laboratories is developing a process that applies oxygen directly to oxidize the sulfur. Although some coal is lost to oxidation, this is balanced by the reputed 90 percent sulfur removal; legal problems have delayed process implementation.

Organic sulfur can also be removed by several techniques, all of which are still on a laboratory scale. Both the Bureau of Mines and Battelle are investigating sodium hydroxide leaching, with preliminary results indicating up to 70 percent organic sulfur removal. The KVB Corp. is developing an oxidation process using a gaseous mixture of N_2, O_2, and NO_3; laboratory results have been encouraging (Ref. 31).

Fluidized Bed Combustion

Fluidized bed combustion (FBC) is still developmental, but experts project that it will have a significant future impact on the power generation field starting in the early to mid 1980s. This technique uses a bed of limestone (or dolomite) that is suspended, or "fluidized," by underfire air jets; coal (or other fuel) is injected into this bed for combustion. The high bed turbulence characteristic of FGC is an aid to more complete combustion at lower operating temperatures. The optimum reported combustion temperature for FBC is in the range of 750 to 950°C, while temperatures as high as 1400 to 1500°C are commonly used in pulverized coal combustion.

While combustion efficiency is the primary consideration, the potential for reduced air pollution emissions is also attractive. Nitrogen oxide emissions from FBC are inherently low, which makes FBC superior in this respect. Sulfur dioxide emissions are also reduced due to the presence of the limestone bed, which acts as an adsorbent. Unlike the relatively inefficient method of limestone injection into a conventional boiler, FBC enhances adsorption through greater turbulence, good gas/solids contact, and long sorbent residence time in the bed, while remaining at temperatures below the "dead burning" level of limestone or dolomite. Eventually all coal ash is entrained in the flue gas as particulate matter. The amount of sorbent bed lost to the flue gas is dependent on gas velocity.

The United States is concentrating on FBC research through a number of public (EPA, ERDA, and TVA) and private (EPRI) institutions. In the past few years, laboratory and pilot scale operations have been constructed, which operate at both atmospheric and higher pressures. The state-of-the-art in FBC is rapidly advancing toward full-scale operational status. Recently, a 30-MW boiler operating at atmospheric pressure was started up by ERDA at Rivesville, West Virginia. Other facilities ranging from a 100,000-lb steam/hr commercial boiler to a 200-MW utility plant are in the design stages.

Many operational problems are anticipated with FBC, although premature troubleshooting has, in the opinion of some, slowed the advancement of the art. Potential problems include the following:

- Solids handling; i.e., feed coal distribution and bed material size control;
- Erosion of internal parts due to higher turbulence and particulate loading; and
- Limestone regeneration (reuse is known to be a problem) - moderate feedstock losses are anticipated in large-scale systems, although the existing regeneration technology is presently being studied for improvement (Ref. 7).

Coal Gasification

A promising technology for the use of high sulfur coal involves low BTU coal gasification. Gasification has two advantages over FGD. First, the gas is produced under reducing conditions so the sulfur is converted to more easily removed H_2S. Second, the process can be performed at high gas pressures, allowing for use of combined power cycles with higher efficiencies. However, there are many unanswered environmental and technical questions that need to be resolved. In addition, the costs for coal gasification are high compared to conventional fuel firing.

Three basic reactors have been developed for the gasification of coal. These are fixed-bed (or moving-bed), fluidized-bed, and entrained (or suspension) reactors. Gasification of coal in molten-iron and molten-salt baths has also been studied. In a fixed-bed reactor, the gasifying medium is passed countercurrent to the coal with ash removal from the bottom and co addition at the top. The bed is fixed in that, ideally, conditions remain constant with time throughout the bed. If the velocity of the gasifying agent and the size of the coal particles are such that the bed behaves as a fluid, the system is called a fluidized bed. An entrained system operates with pulverized coal particles carried by the gasifying agent (Ref. 84). Examples of commercially available coal gasification systems are the Lurgi, Kopper-Totzek, and Winkler processes.

The Lurgi dry-ash gasifier is a fixed bed, pressurized generator that is made up of three main parts: the coal hopper, the reactor, and the coal ash lock. Coal is fed from the top of the generator through the coal hopper and into the reactor. In the reactor, the coal contacts a mixture of oxygen and steam (or air and steam) counter-currently. The oxygen and steam are injected into the lower region of the gasifier. The mixture is proportioned to control the temperature in the reactor so that the formation of clinkers, due to the fusion of ash, can be avoided. A mechanical stirrer keeps the coal and ash separated. The ash is continuously removed from the bottom through the ash lock after being separated by a revolving grate. The fuel bed is heated by the rising gases, and the volatile compositions of coal are vented as part of the raw gas from the top of the gasifier. Required operating conditions include a pressure range from 240 to 315 N/cm^2, a temperature range from 620 to 760^{o}C, and a residence time of almost one hour. The crude gas leaves the gasifier at a temperature of 370 to 595^{o}C and contains tars, oil, naphtha, phenols, sulfides, and ammonia along with coal and ash dusts and a variety of other chemical compounds.

In the Kopper-Totzek process, a well-mixed feed of coal and oxygen is injected from both sides of the reactor. The opposite jet configuration creates a high degree of turbulence that increases the reaction rate significantly. The combustion reaction takes place very close to the injection point, while the reduction reaction continues in the remaining space. Due to the concurrent flow of the reactants, the hydrocarbons produced at low temperatures are passed into a very high temperature zone where they decompose rapidly. As a result, there is no coagulation of coal particles. Some unreacted carbon and about 50 percent of the ash, entrained in the hot gas (980 to 1260^{o}C), leave the gasifier. This gas passes through the waste heat boiler, the dust collector, the wet scrubbing tower, and the disintegrator. The gas can be used directly or compressed for future use or further processes. The remaining ash in the gasifier is slagged and gets tapped off from the bottom of the reactor.

The Kopper-Totzek process is very versatile. It can gasify many types of fuel, including petroleum coke, tars, heavy residual oils, and all ranks of coal; the transfer from solid to liquid fuel requires only a change in the burner head. A second advantage is that the process is very low in air pollution generation.

The Winkler process is presently the only commercially available fluidized bed gasifier. There are currently 36 Winkler installations operating at 16 plants. This process can be used to gasify a variety of solid fuels, including brown coal, brown coal-char, semicoke, caking, and, most commonly, subbituminous coal or its coke. The Winkler reaction is a fluidized bed, operating at or near atmospheric pressure and from 800° to 1000°C. The temperature is varied to suit the reactivity of the fuel, with maximum temperature limits being set by the ash sintering temperature (Ref. 106).

Combined cycles power plants have been proposed for pressurized gasifiers. In this type of system, the high pressure fuel gas is expanded through a turbine-generator and then burned in a boiler to produce steam; the use of both steam and fuel gas to generate electricity improves system efficiency. The only pressurized gasifier that is commercially available is the Lurgi process; its limited capacity would make multiple units necessary to generate sufficient quantities of gas and electric power to replace existing boiler equipment.

Table 9 shows the developmental stage of the various coal gasification concepts. The cost of coal gasification is said to compare favorably to conventional solid fuel-fired installations. One source quotes a new installation cost at $280/kW, and retrofit costs have ranged from $110 to $498/kW (Ref. 161).

TABLE 9.* STAGE OF DEVELOPMENT OF TYPICAL LOW BTU GASIFICATION PROCESSES

	Concept		Bench		Pilot		Demo.		Commercial		Coal Condition		HHV*	Type of Reactor			Operating Pressure		
			Const.	Test	Const.	Test	Const.	Test	Const.	Test				Fluid Bed	Entrained Bed	Moving Bed	0-15 psig	100-500 psig	1000-1500 psig
	1	2	3	4	5	6	7	8	9	10	Caking	Non-Caking							
Atgas	X	X	X	X							X	X	100-200 300-500	Molten-iron bath			X		
Bi-Gas	X	X	X	X	X						X	X	100-200 300-500		X				X
Hydrane	X	X	X	X							X	X	300-500	X					X
CO_2 Acceptor	X	X	X	X	X	X					X	X	300-500	X				X	
Koppers Totzek	X	X	X	X	X	X	X	X	X	X	X	X	300-500		X		X		
Lurgi	X	X	X	X	X	X	X	X	X	X		X	100-200 300-500			X		X	
Molten Salt	X	X	X	X							X	X	300-500	Molten-salt bath					X
Synthane	X	X	X	X	X						X	X	100-200 300-500	X					X
U-Gas	X	X	X	X	X	X					X	X	100-200	X				X	
Union Carbide	X	X	X	X	X						X	X	300-500	X				X	
Wellman Galusha	X	X	X	X	X	X	X	X	X	X	X	X	100-200 300-500			X	X		
Westinghouse	X	X	X	X	X								100-200	X				X	
Winkler	X	X	X	X	X	X	X	X	X	X	X	X	100-200 300-600	X			X		

* Higher Heating Value (Btu/scf)

*Ref. 106

SECTION VI

WASTE CHARACTERIZATION

PARAMETERS WHICH DETERMINE SLUDGE CHARACTERISTICS

The physical and chemical properties of FGC sludges are influenced by many interrelated parameters. These interrelationships and the relative importance of each under a given set of conditions are not completely understood. However, general statements can be made about the various parameters and how they interact. The chemical composition of the solid and liquid phases is a function of the following parameters:

- Fuel type and composition
- Boiler type, design and operation
- Fly ash and bottom ash removal systems and their relation to sludge disposal
- FGC system type, design and operation
- FGC reagent and input water

The physical properties of the sludge depend primarily upon the same parameters but with a different functional dependence.

Fuel Type and Composition

The composition of the fuel is a primary factor in determining the concentration of trace elements in the sludge and the amount of sludge generated. Generally, an increase in the concentration of a particular trace element in the fuel results in an increase in its concentration in the sludge. Sulfur concentration in the fuel will obviously directly affect the quantity of sludge solids generated, since a largely stoichiometric reaction occurs between the sulfur oxides and the sorbent. The relationship between excess combustion air and coal sulfur content combined with pH is most important. Due to the predominance of high sulfur coal-based FGD systems, most FGD sludges have a sulfate/sulfite ratio of less than unity. The few systems generating a predominantly sulfate sludge are either (1) located in the western U.S. and burn low sulfur coals, or (2) employing some method of forced oxidation.

Coal is generally the primary source of trace metals in FGD sludge liquors. Certain of the trace metals condense on the surface of fly ash particles and are readily available for subsequent dissolution in the sludge. The more volatile trace metals encountered (arsenic, selenium, and mercury in particular) may not condense readily within the flue gas cleaning system; their presence in the sludge liquor is strongly dependent upon the particulate collection efficiency of the scrubbers.

Boiler Type, Design, and Operation

Boiler type, design and operation influence the partitioning of various fuel impurities between the bottom ash, fly ash and vapor phases. Chemical form, e.g., oxidation state, etc., of specific impurities and their location in the ash particles (within or upon the surface of the particle) depends upon the time-temperature profile, flame chemistry, and ash characteristics. These interactions are not well understood at the present time.

Fly Ash and Bottom Ash Addition

Co-disposal of fly ash and bottom ash with FGC sludge will affect both the chemical and physical properties of the sludge. Addition of ash can improve physical properties for subsequent disposal because the resulting sludge is more stable, has higher load-bearing strength, and is more erosion resistant.

Since fly ash contains a large percentage of the trace metals from the fuel, the amount and size distribution of the fly ash entering the sludge will affect the chemical properties. If all fly ash were removed ahead of the scrubber, the concentration of many impurities would be reduced. The exceptions are those impurities which either can exist in the vapor phase at the scrubber or those impurities originating in the sorbent or makeup water. The oxidation rate of sulfite to sulfate in the scrubber system depends primarily upon the sulfur/oxygen ratio in the flue gas. Although certain metallic ions act as catalysts for this oxidation, very complex interactions will also occur between the fly ash entering the sludge and the nucleation and growth of calcium sulfite and sulfate crystals. These interactions are not well understood at the present time.

FGD System Type, Design and Operation

The design and operation of the FGD system will affect the sludge characteristics in various ways, just as the efficiency of particulate collection in the scrubber will affect the chemistry of the sludge. The details of system design (e.g., liquid to gas ratio, holding tank design, and method and location of reagent addition) will affect the nucleation and growth of crystalline phases. In particular, the amount of supersaturation at the point of reagent addition will affect the nucleation and size distribution of the resulting crystals, which in turn will affect both the permeability and load bearing strength of the resulting sludge. Some understanding of these interactions is being developed through present EPA-sponsored test programs.

Operational variables in conjunction with fuel characteristics and scrubber design will have an impact on the sulfate/sulfite ratio. Decreasing the pH will generally increase the oxidation rate. In practice, the range of these operating variables is limited by possible internal corrosion and scaling.

The ratio of calcium sulfate to calcium sulfite (better known as sulfate/sulfite ratio) in the solid phase is important to certain physical properties of the sludge. Sulfate is formed by oxidation of sulfite, usually occurring within the scrubber loop. Although a certain amount of sulfite oxidation occurs in all lime/limestone systems, sulfate sludges are generally formed in scrubbers with one or more of the following characteristics:

- Low concentrations of sulfur dioxide in the inlet flue gas, resulting in a high oxygen/sulfur dioxide ratio;
- The presence of oxidation catalysts, such as metals from fly ash;
- Long gas retention times in the scrubber system (e.g., deep bed, multiple stages, etc.);
- An added oxidation stage, such as a special aerator;
- A low pH in the scrubber liquor.

Fly ash collection in FGD-equipped power plants is sometimes accomplished with the same scrubber or a second scrubber in series using a common liquor reservoir; plants of this type generate sludge with a high fly ash content. Fly ash is typically a major source of trace metals found in FGD sludge. Fly ash may also be added to the sludge if collected dry, thereby improving sludge handling characteristics by increasing the solids content of the disposed mixture.

Unreacted lime and limestone are often present in significant amounts in FGD sludge. Limestone due to its low reactivity, is often used in higher stoichiometric quantities (1.2 to 1.5). Lime systems and double alkali systems which incorporate lime to regenerate sodium both operate at a near-stoichiometric ratio with sulfur, thereby wasting little lime in the sludge discharge.

Whether the system is operated in an open or closed loop mode makes a significant difference in the chemical properties of the sludge, particularly the high soluble salt content characteristics of a closed loop operation (continuous recirculation).

FGC Reagent and Input Water Quality

The input water and sorbent are sources of impurities which will affect the chemical composition of the sludge. In general, the makeup water quality requirements for FGC equipment are lower than for other systems in a power plant. Any water reuse in a power plant would probably use the FGC system as the water sink. Depending upon the cost and value of internal water reuse, certain plants use low quality water for scrubber makeup. The use of cooling towers blowdown for makeup water is one common example; if the scrubber system is operated in a closed-loop mode, all the salts entering the cooling tower with the freshwater makeup will end up in the scrubber sludge. Even in cases where some of the impurities in the input water are removed by water treatment, the resulting sludge may be carried over to the scrubber and thus transfer the impurities from the input water to the scrubber sludge.

In a similar manner, the scrubber sorbent material can affect sludge characteristics through trace metal inclusion and the characteristic pH of the slurry. The lime systems generally produce a higher sulfite content sludge than limestone systems. The concentration of trace metals in the sorbent is specific to each sorbent and its source.

Conclusion

From the above discussion it is clear that many factors affect the chemical and physical characteristics of FGD sludge. Several of these factors can be controlled with proper plant operation. This might be construed to mean that sludge characteristics can be modified to suit the disposal method and specific site characteristics. However, the power plant and associated gas cleaning equipment costs are generally much greater than sludge disposal costs. Overall system cost minimization will therefore generally require designs which minimize the FGC system cost rather than optimize the sludge characteristics.

CHEMICAL, PHYSICAL, AND BIOLOGICAL CHARACTERISTICS OF FGD SLUDGE

The physical and chemical characteristics of FGD sludge are important to an effective disposal operation and have been the subject of most disposal-related research efforts to date. An extensive data base is becoming available. Biological characteristics are of limited importance since the waste is inorganic; research in this area is currently lacking.

Chemical Characteristics

The by-products of non-regenerable FGD systems are typically composed of four major constituents: calcium sulfate hemihydrate and/or dihydrate (due to mixed crystallization), calcium sulfite hemihydrate, unreacted sorbent, and fly ash. The relative amounts of these constituents are determined by the various scrubber and plant operating parameters discussed in the previous section. Table 10 shows the wide variation in sludge solid phase composition encountered in different FGD systems.

The solid phase of FGD sludge can also contain a variety of trace metals. These metals can come from several sources, including fly ash, sorbent, makeup water or vapors in the flue gas itself. The metals which are contained in fly ash generally remain in the solid phase. Those which form on the ash surface are often dissolved in the waste slurry and enter the liquid phase; from there they may precipitate either as pure compounds or with the sulfate/sulfite crystals.

The liquid phase of FGD sludges is important due to its potential as leachate. The sludge liquors typically contain ions of sulfate, sulfite, chloride, calcium, magnesium, and various trace chemical species. The total dissolved solids (TDS) concentration in FGD sludges is a function of their equilibrium levels in the scrubber system, with TDS concentration in excess of 20,000 ppm being quite common in closed-loop operations. Table 11 lists the typical range of values for various species concentrations in the liquid phase.

Physical Characteristics

The physical characteristics of FGD sludge solids are important to treatment process operations, disposal methods, and potential environmental effects. Of special interest are crystal morphology, bulk density, viscosity, and compressibility. Environmental considerations include permeability, settling characteristics, and load bearing strength. Table 12 summarizes the importance of various sludge properties to FGD sludge disposal operations and Table 13 lists some typical values for those and other related parameters.

Crystal Morphology--

Crystal morphology has perhaps the strongest influence on FGD sludge physical characteristics. Calcium sulfite hemihydrate is the predominant solid phase in most sludges.

TABLE 10.* COMPOSITION OF SLUDGE FROM OPERATING SO_2 SCRUBBERS

Facility	Scrubber Sorbent	Sludge Composition (dry basis), wt percent				Comment
		$CaSO_3 \cdot \frac{1}{2}H_2O$	$CaSO_4 \cdot 2H_2O$	$CaCO_3$	Fly Ash	
Lawrence	Limestone	10	40	5	45	
Hawthorn 3	Limestone	20	25	5	50	
Hawthorn 4	Limestone	17	23	15	45	
Will County 1	Limestone	50	15	20	15	
Stock Island	Limestone	20	5	74	1	Oil fired
La Cygne	Limestone	40	15	30	15	
Cholla	Limestone	15	20	0	65	14% $CaS_2O_3 \cdot 6H_2O$
Paddy's Run 6	Lime	94	2	0	4	
Mohave 2	Limestone	2	95	0	3	
Shawnee 1	Limestone	19-23	15-32	4-14	20-43	
Shawnee 2	Lime	50	6	3	41	
Phillips	Lime	13	19	0.2	60	9.8% CaS_3O_{10}
Parma	Dual Alkali	14	72	8	7	
Scholz 1A	Dual Alkali	65-90	5-25	2-10	0	
Utah	Dual Alkali	0.2	82	11	9	
Colstrip	Lime/Alkaline Ash	0-5	5-20	0	40-70	5-30% $MqSO_4$

*Ref.96, 129

TABLE 11.* LEVELS OF CHEMICAL SPECIES IN FGC SLUDGE LIQUORS AND ELUTRIATES

Species	Eastern Coals Range in Liquor (ppm)	Eastern Coals Median (ppm)	Western Coals Range in Liquor (ppm)	Western Coals Median
Antimony	0.46-1.6	1.2	0.09-0.22	0.16
Arsenic	<0.004-1.8	0.02	<0.004-0.2	0.009
Beryllium	<0.0005-0.05	0.014	0.0006-0.14	0.013
Boron	41	41	8.0	8.0
Cadmium	0.004-0.1	0.023	0.011-0.044	0.032
Calcium	470-2600	700	420-(~45,000)(2)	720
Chromium	0.001-0.5	0.02	0.024-0.4	0.08
Cobalt	<0.002-0.1	0.35	0.1-0.17	0.14
Copper	0.002-0.4	0.015	0.002-0.6	0.20
Iron	0.02-0.1	0.026	0.42-8.1	4.3
Lead	0.002-0.55	0.12	0.0014-0.37	0.016
Manganese	<0.01-9.0	0.17	0.007-2.5	0.74
Mercury	0.0009-0.07	0.001	<0.01-0.07	0.01
Molybdenum	5.3	5.3	0.91	0.91
Nickel	0.03-0.91	0.13	0.005-1.5	0.09
Selenium	<0.005-2.7	0.11	<0.001-2.2	0.143
Sodium	36-20,000(1)	118	1650-(~9,000)(1)	--
Zinc	0.01-27	0.046	0.028-0.88	0.18
Chloride	470-5000	2300	1700-43,000(2)	--
Fluoride	1.4-70	3.2	0.7-3.0	1.5
Sulfate	720-30,000(1)	2100	2100-18,500(1)	3700
TDS	2500-70,000(1)	7000	5000-95,000(2)	12,000
pH	7.1-12.8	--	2.8-10.2	--

(1) Levels of soluble sodium salts in dual alkali sludge (filter cake) depend strongly on the degree of cake wash. The highest levels shown reflect single measurements on an unwashed dual alkali filter cake.

(2) Levels of soluble chloride components in sludges are dependent upon the chloride-to-sulfur ratio in the coal. The highest levels shown are single measurements for a western limestone scrubbing system.

* Ref. 139

TABLE 12. SLUDGE PROPERTIES AND THEIR RELATION TO SLUDGE DISPOSAL

Physical Property	Importance to Disposal
Crystal Morphology	Determines to some extent the settling, dewatering, and water retentive characteristics of the sludge; also regulates the thixotropic behavior typical of some sludges.
Bulk Density	Determines disposal capacity and transportation requirements.
Permeability	Determines the rate at which liquid will flow through the sludge; rate-controlling step in leaching when the sludge permeability is less than that of underlying soil.
Settling Characteristics	May affect rate of release of leachate to surrounding soil, as well as mechanical dewatering capability.
Compressibility	Reclamation of the disposal site as well as increasing site design capacity.
Viscosity	Gives some indication of the flow properties of the sludge, although sludges are non-Newtonian fluids and are subject to additional flow considerations.

TABLE 13.* PHYSICAL PROPERTIES OF SELECTED RAW FGD SLUDGES

Sample No.	Specific gravity[a]	Bulk density (kg/m^2)[b]	Oven-dry unit wt (kg/m^2)[b]	Water content (%)[b]	Porosity (%)[b]	Void ratio[b]
1	2.45	828.2	800.9	3.3	67.3	2.059
2	3.27	1017.2	679.2	49.6	79.2	3.815
3	3.99	2518.1	2452.4	2.7	38.5	0.627
4	2.73	1010.8	978.7	3.2	64.2	1.789
5	2.90	837.8	754.5	11.0	74.0	2.844
6	2.67	1425.6	1374.4	3.7	48.5	0.943
7	3.00	889.0	815.3	9.1	72.8	2.679
8	2.82	1030.0	919.5	12.1	67.4	2.067
9	2.95	759.3	725.6	4.6	75.4	3.065

[a] Value determined from one specimen.

[b] Average value determined from three specimens.

[c] Disintegrated during first cycle.

[d] Tangent of "straight" portion of stress-strain curve.

*Ref. 104

Sulfite crystals usually form in single flat plates, although spherical aggregated forms are also observed. In contrast, calcium sulfate dihydrate solidifies in blocky crystals. A limited amount of sulfate is soluble in the sulfite crystals, thereby making an unsaturated mode of operation possible.

The sulfite crystaline species is generally described by the formula:

$$(CaSO_3)x \cdot (CaSO_4)y \cdot zH_2O$$

where x is much greater than y, and z approaches 0.5 (Ref. 28).

Research at TVA has shown that the scrubber sorbent can affect the resulting crystal form (Ref. 28). Sulfite crystals formed in limestone systems are generally of the flat plate variety, although aggregated forms ("rosettes") are also observed. The length-width-thickness ratio of these crystals is approximately 25:20:1 and varies only by a factor of 2 or 3 between samples. In contrast, sulfite crystals formed in lime systems are almost exclusively spherical and show no variation in crystal size within a sample.

FGD sludge crystals are typically between 1 and 200 microns in diameter. FGD sludges have been classified for study purposes as silt (ML) under the Unified Soil Classification System and as silt and silt loam under the U.S.D.A. systems (Ref. 106). Figure 9 displays the typical range of grain sizes for FGD sludges.

Other solid phases encountered in FGD sludges include fly ash and mixed sulfate/sulfite crystals. Fly ash is typically formed in spheres from submicron to more than 1,000 microns in size; sulfite crystal growth on fly ash is rarely encountered.

The impact of crystal morphology on sludge treatment and disposal, as well as on other physical characteristics, is discussed in the following subsections and Section VII.

Bulk Density--

The bulk density of FGD sludges is another important physical characteristic. Bulk density determines such disposal-related parameters as compressibility, landfill volume requirements, permeability, and to some extent, compaction strength.

Bulk density by definition refers to the weight per unit volume of a bulk granular solid material; true density is the density of the individual particles composing the material. Because calcium sulfate/sulfite is denser than water, dewatering to a certain point will increase the density of the overall sludge. Beyond that point, interstitial water is replaced by

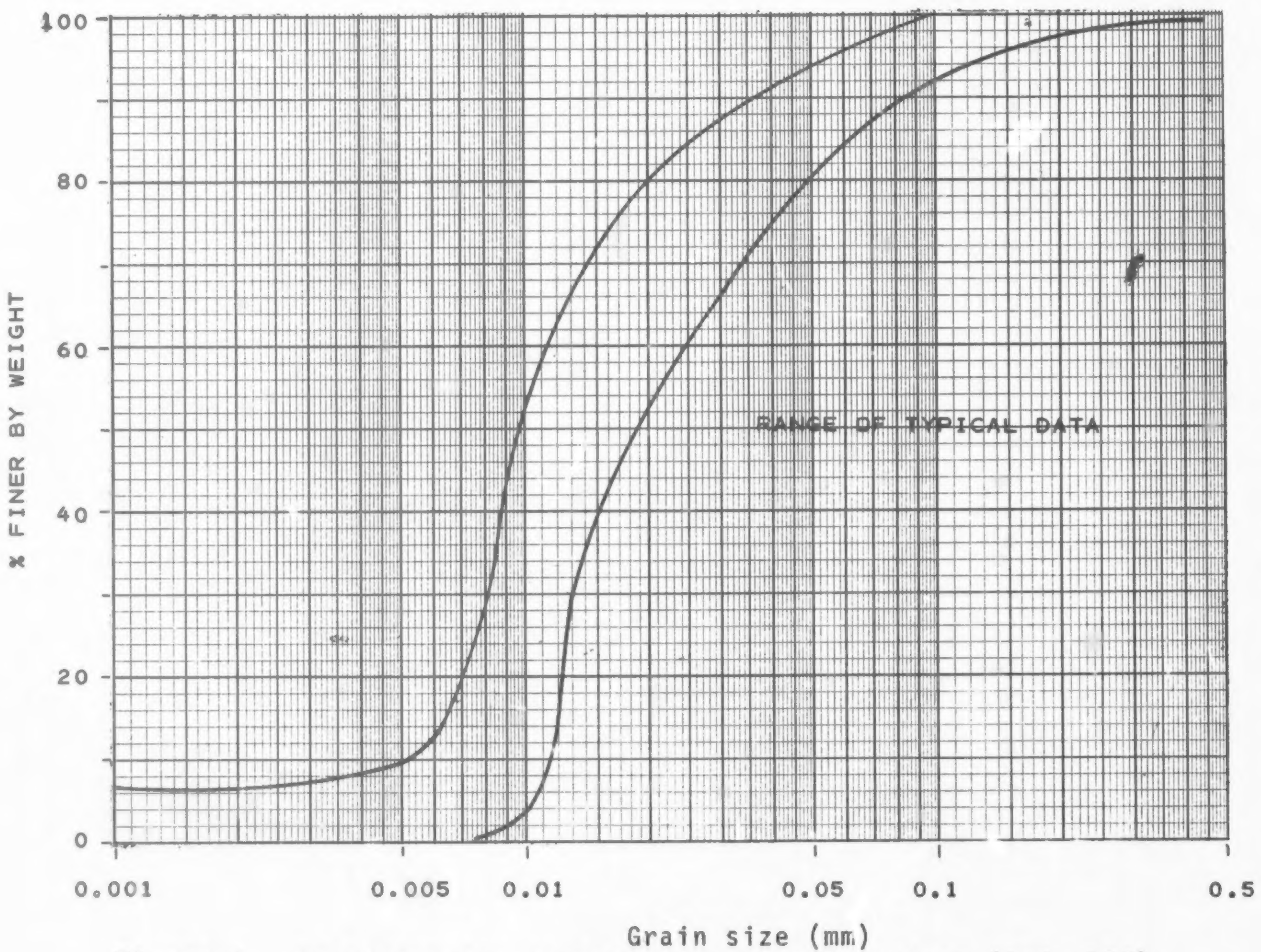

Figure 9. Particle-size distribution of FGD sludges (Ref. 106).

air voids which cause a decrease in density. The point at which maximum (bulk) density can be achieved by compression is termed the "optimum moisture content."

Figure 10 displays the relationship between moisture content and bulk density for two FGD sludges, a high sulfate sludge from SCE Mohave and a high sulfite sludge from TVA Shawnee. This figure indicates that the sulfite sludge has a higher optimal moisture content than the sulfate sludge.

Table 14 compares the true densities with the bulk densities of several sludge samples; also shown is the effect of dewatering on the density of the sludges. Note that only the Mohave sulfate sludge exceeded the maximum bulk density following mechanical dewatering; this low dewatering effectiveness is typical of most full-scale mechanical dewatering operations.

Permeability--

Permeability, another important physical parameter, is related to the rate of flow of liquids through the material under a hydraulic driving force. This parameter enters into the calculation of the mass transport rate of contaminants from the disposal site to the groundwater as discussed in Appendix B. Before discussing the reported values of the permeability of either untreated or treated sludges, it is useful to discuss the techniques of measurement and their potential applicability to field situations under various conditions.

Permeability data as reported in this document is based upon laboratory experiments of either falling head or constant head permeability tests under saturated flow conditions. In this type of experiment, a sample of the material is placed in a container with a bottom drain. A head of water is applied above the sample with the rate of flow being measured either at constant head or falling head. These flow rates are related to the permeability of the specimen through the appropriate equations.

This type of measurement is quite accurate. The values of permeability are independent of hydraulic head for course grained materials which do not compact under the applied hydraulic head. For very fine grained materials which are subject to compaction, the measured permeability depends upon the hydraulic head applied.

When measuring very low permeabilities in solid materials, edge effects (where most of the measured flow is around the sample rather than through the sample) can be a significant source of error in the measurements if not accounted for in the design. Cracks in solid samples can also create non-reproducible results.

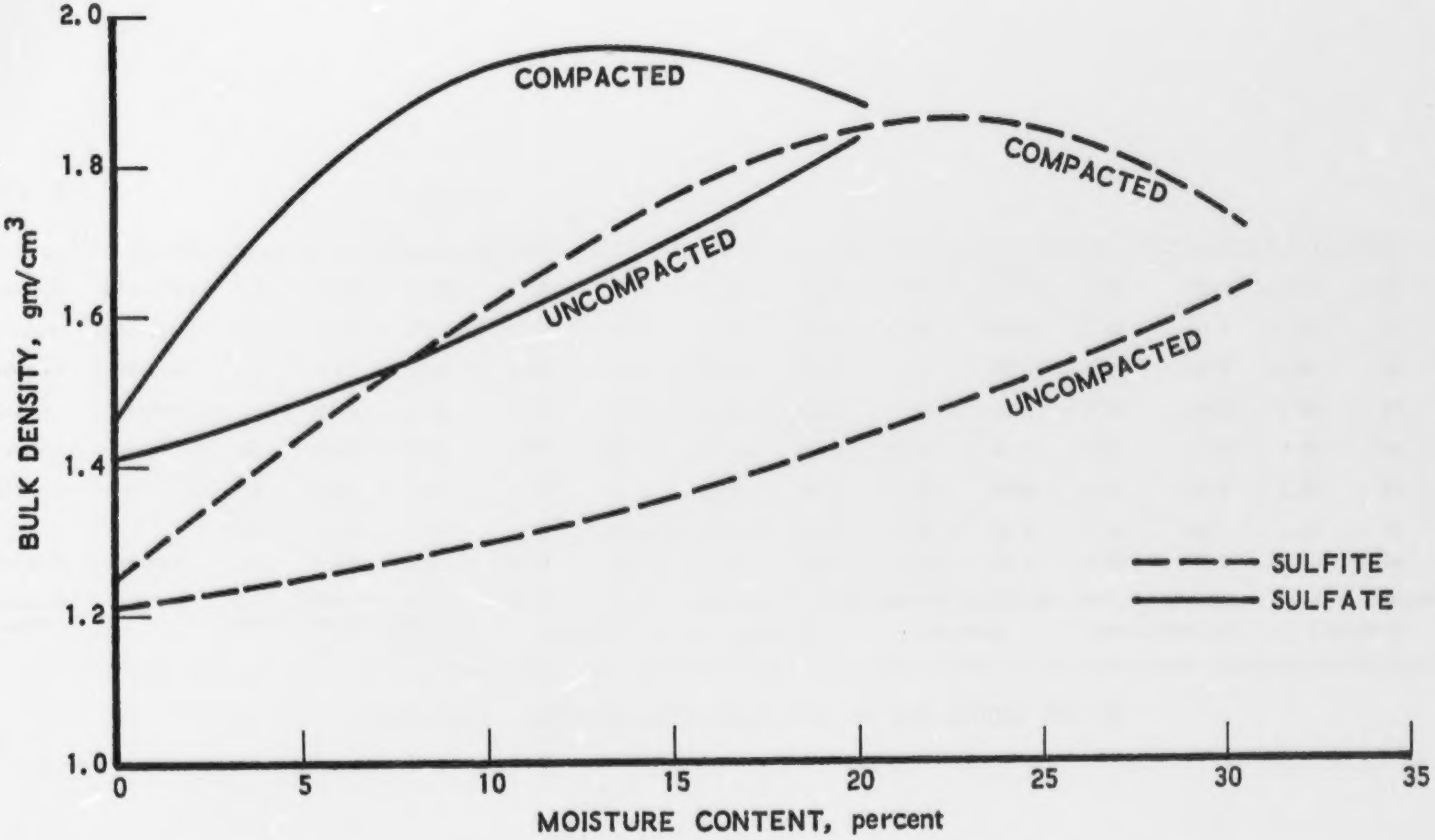

Figure 10.* Bulk density versus moisture content for selected sulfate (Mohave) and sulfite (Shawnee) FGD sludges.

*Ref. 96

TABLE 14.* TRUE AND BULK DENSITIES OF FGC SLUDGE SOLIDS

Plant Location	Process	Flyash (%)	True Density (g/cc)	Dry Bulk Density (g/cc)	Settled		Drained		Filtered		Centrifugation		Saturation	
					Density	% Solids	Density	% Solids	Density	% Solids	Density	% Solids	Density	% Solids
Eastern	Limestone	20	2.48	1.20	1.45	45.0	1.51	51.7	1.65	65.0	1.56	55.8	1.73	70
		40	2.45	1.21	1.52	52.9	1.53	58.3	1.70	65.9	1.56	63.3	1.73	70
Eastern	Lime	36	2.53	1.02	1.34	43.4	1.37	45.3	1.55	56.0	1.37	49.9	1.62	63
Eastern	Lime	60	2.50	1.12	1.40	47.6	1.47	54.2	1.52	57.0	1.47	57.2	1.67	67
Western	Limestone	59	2.53	1.33	1.39	46.7	1.44	50.9	1.48	53.4	1.60	60.9	1.80	74
Western	Limestone	3	2.53	1.46	1.65	66.6	1.67	67.2	1.78	80.3	1.86	75.0	1.87	78
Eastern	Dual Alkali	7	2.45	1.30	1.26	40.0	1.39	43.9	1.57	57.8	1.40	50.9	1.76	74
Western	Dual Alkali	9	2.60	1.16	1.29	37.4	1.30	37.8	1.38	43.1	1.54	62.2	1.71	67

* Ref. 2

When attempting to use permeability data in a mass transport model, differences between saturated and unsaturated flow must be accounted for. When the specimen is not initially saturated with water, the void space is filled with air. When water tries to flow through the sample, the air may be displaced or trapped in some of the voids. Depending upon the hydrophilic or hydrophobic nature of the internal surfaces of the sample, drastically different results may be obtained. On one extreme, a fine grained, hydrophobic material would measure zero permeability for low hydraulic heads. By applying sufficient hydraulic head, the material would become saturated and the surface tension forces would be overcome; in this case the permeability would increase to the saturated value after all the air is forced out of the specimen.

For strongly hydrophilic materials, the capillary tension can make an unsaturated material behave as though it has a very high permeability until it becomes saturated. The above factors must be considered when translating laboratory data to field situations.

FGD sludge permeability is dependent both upon size distribution and particle shape. Settled sulfite sludge is generally less permeable than sulfate sludge do to the irregular shape of the sulfite crystal aggregates. Settled and drained FGD sludges exhibit permeabilities of 10^{-3} to 10^{-4} cm/sec; light compaction will decrease this to 10^{-5} cm/sec, and even lower permeabilities have been attained on the laboratory scale using greater compaction and more extensive dewatering.

The presence of fly ash will decrease sludge permeability. The smaller fly ash particles fill in the sludge interstices, thereby blocking the movement of fluid through the media. Permeabilities of about 10^{-6} cm/sec have been achieved for a sulfite sludge mixed with fly ash; this is thought to be the minimum permeability achievable with untreated sludge. Table 15 lists the permeabilities of several FGD sludge samples.

Compressibility--

The compressibility, or compactibility, of FGC sludge is an important parameter when planning for site reclamation. The amount of compaction which can be achieved is dependent upon moisture content, crystal morphology, and compaction force as mentioned before, the optimum moisture content is that at which the sludge can be compacted to the greatest extent (corresponding to maximum compacted bulk density).

Studies of FGD sludge compressibility are documented in literature; one found that a sludge with equal quantities of sulfate and sulfite could be compacted to 1.3 g/cm^3 at 77 percent solids but only 1.2 g/cm^3 at 72 percent solids.

TABLE 15.* PERMEABILITIES OF UNTREATED FGC SLUDGES

			Settled		Compacted	
Location	Process	Sample No.	VR[1]	CP[2] (cm/sec)	VR[1]	CP[2] (cm/sec)
Eastern	Limestone	1	1.53	1.02×10^{-4}	1.27	7.78×10^{-5}
		2	2.07	3.37×10^{-5}	1.56	1.11×10^{-5}
Eastern	Lime	1	1.83	1.74×10^{-4}	1.68	5.27×10^{-5}
		2	1.65	6.01×10^{-5}	1.42	1.07×10^{-5}
		3	1.25	1.28×10^{-4}	0.97	7.4×10^{-5}
Western	Limestone	1	0.96	3.25×10^{-5}	0.63	1.44×10^{-5}
		2	1.20	1.85×10^{-5}	1.20	1.11×10^{-5}
		3	0.75	8.3×10^{-4}	0.50	9.1×10^{-5}
Eastern	Dual Alkali	1	5.11	7.81×10^{-5}	4.17	2.51×10^{-5}
		2	2.19	2.46×10^{-4}	1.95	8.06×10^{-5}
Western	Dual Alkali	1	2.77	9.8×10^{-4}	2.61	1.33×10^{-4}

[1] Void Ratio

[2] Coefficient of Permeability

*Ref. 1

Similarly, a study of double alkali sludge achieved 1.15 g/cm^3 at 75 percent solids. Another study dealing with the effects of sulfate versus sulfite on compressibility as shown in Table 16 found that higher sulfate concentrations in the solid phase reduced compressibility significantly (Ref. 64).

Laboratory experiments by the Aerospace Corporation have achieved compacted bulk densities in excess of 1.44 g/cm^3; this represents a volume reduction of 25 percent for pure sulfite sludge but only 7 percent for sulfate sludge (Ref. 96). This study also estimated the optimum moisture contents to be 10 and 20 percent for sulfate and sulfite sludges, respectively. The actual field compaction of the two sludge types will not result in such a marked difference in compaction due to varying compaction efficiencies and compacting loads.

Load Bearing Strength--

Load bearing strength is a partial function of compressibility, but also depends heavily upon the moisture content of the sludge. The Aerospace studies have shown that sulfate sludge compaction strength increases rapidly from 2.0 x 10^5 to 2.0 x 10^6 dynes/cm^2 below 35 percent moisture content. Since this moisture content can be achieved by mechanical dewatering, sulfate sludge can be made to support men and equipment if compacted. Japanese experience with high sulfate sludge (gypsum) production also indicates that this material will readily support grading equipment (Ref. 139).

The load bearing strength of TVA sulfite sludge at Shawnee was shown to increase gradually with decrease in moisture content. At 30 percent moisture content, the strength begins to increase markedly corresponding to the peak viscosity. The load bearing capacity at this point was 2.1 to 2.4 x 10^6 dynes/cm^2. Even at low moisture content, however, the sludge will liquify if jarred or vibrated. Figure 11 displays the results of the Aerospace strength tests (Ref. 139).

Despite the variation in FGD sludge load bearing strength between sludges, certain generalities can be made. Light compaction will result in only a small improvement of strength. Settlement is unavoidable even after heavy compaction, although landfilled sludge settlement may be less than that of many common soils under these circumstances. Unconfined compressive strength is quite low, typically in the range of 7 to 14 x 10^5 dynes/cm^2.

Settling Characteristics--

The settling and dewatering characteristics of FGD sludge have been observed to be related to sulfite content. During the first stage of settling, referred to as clarification, the rate

TABLE 16.* THICKENER DIAMETER REQUIRED AS A FUNCTION OF CALCIUM SULFATE OXIDATION AND GENERATING CAPACITY

Generating Capacity (MW)	Sludge Production** (tons/day)	Required Diameter (ft)		
		10% Oxid.	50% Oxid.	80% Oxid.
150	53	25	25	27
500	178	46	47	49
1000	356	65	66	69

* Ref. 64

**Based on 130 tons/MW year.

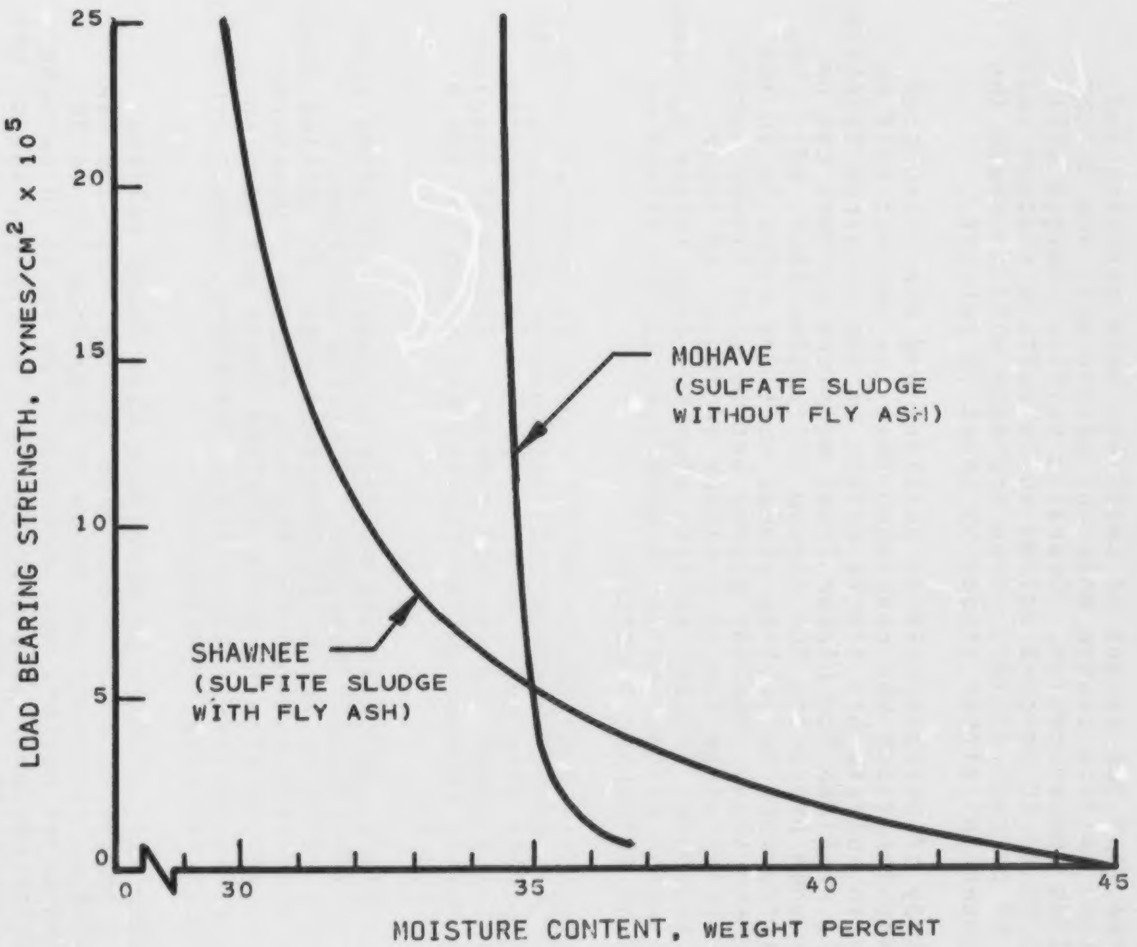

Figure 11. FGD sludge load bearing strength.

*Ref. 128

at which particles settle out of suspension is dependent upon crystal size and shape. Fully hydrated gypsum is the superior settling crystal due to its blocky structure. The flat plate structure of sulfite crystals results in water retention and a slower settling rate.

In the last two stages of settling, zone settling and compression, sulfite sludge does not settle well due to the lower solids concentration. Overall, sulfite sludges will settle to 25 to 40 percent solids while sulfate sludges settle to 60 to 65 percent solids. Free drainage will increase the solids content of either sludge by about 10 percent.

A study of sulfate/sulfite settling and the associated design considerations has concluded that the percent sulfite oxidation to sulfate has little effect on the required thickener diameters, provided the higher final moisture content can be tolerated when preparing for vacuum filtration (Ref. 64). The primary difference in sulfite sludge settling rates is in the crystal plate size. Smaller plates entrap more liquor during the compression stage due to a higher incidence of inner-particle touching; thicker sulfite slurries take longer to reach the compression stage. Table 16 demonstrates the effect of oxidation on thickener diameter.

Viscosity--The viscosity of FGD sludge is important both in terms of flow characteristics and load bearing properties. FGD sludge viscosity is a function of moisture content, crystal morphology, and amount of fly ash present. Figure 12 displays the relationship between solids content and viscosity for 9 selected sludges.

FGD sludges, particularly sulfite sludges, are often said to exhibit "thixotropic" behavior. Strictly speaking, a thixotrophic solid is one which liquifies under an applied shear force and resolidifies when the force is removed. Dewatered sulfite sludges do liquify under applied force but tend to remain in a liquid-like state. They, therefore, cannot properly be considered strictly thixotrophic.

Nonetheless, studies by Aerospace have found sulfite sludges to behave in a quicksand-like fashion. For the TVA Shawnee sludge, viscosity was shown to drop from 120 to 20 poise, when water content was increased from 40 to 50 percent. Higher solids contents gave erroneously low results, due to the rapid release of the viscometer disc, as thixotropicity was induced; this characteristic is important to handling considerations (Ref. 139).

In a manner typical of other sulfate sludges, the viscosity of the SCE Mohave sludge was found to increase with decreasing water content, starting at close to 10 poise at 38.5 percent

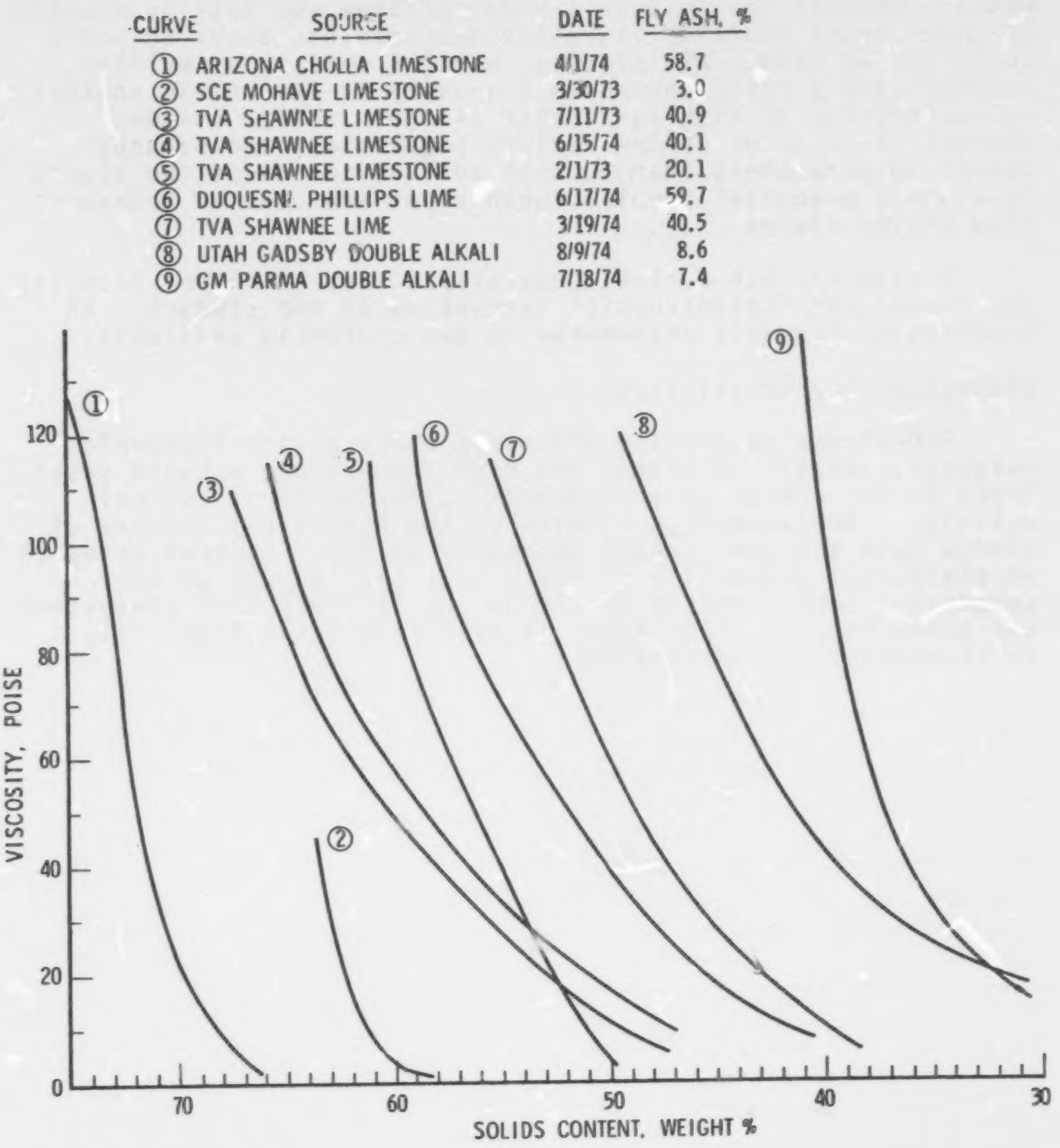

Figure 12.* Viscosities of FGD sludges.

* Ref. 96

water and increasing to approximately 46 poise at 36.5 percent water. Because the sulfate sludge stiffens and settles rapidly at lower water content, viscosity measurements above 50 poise could not be made. All sludges, whether sulfate or sulfite, demonstrated a rapid change in viscosity at the solids content characteristic of each particular sludge. Solids content changes which occur as the various power plant and scrubber operating parameters change, make solidification of the sludge in pipes a potential problem, when pipes are used to transport high solids sludge.

A high fly ash content generally serves to lower viscosity and reduce the "thixotrophic" tendencies of FGD sludges. An explanation for this phenomenon is not currently available.

Biological Characteristics--

FGD sludge generating processes operate with inorganic reagents, caustic solutions and high temperature exhaust gases. These do not create an environment conducive to biological activity. Consequently, studies on the biological aspects of sludge have not been deemed necessary by EPA. Current research on biological properties of FGD sludge has focused on the speculated toxic effects of sludge and leachate upon ecosystems and human health. This topic is discussed in Section VIII, Environmental Considerations.

SECTION VII

TREATMENT AND DISPOSAL TECHNOLOGY

Table 17 shows FGC sludge management practices for utilities and industrial plants currently operating FGC systems. The table is divided into treatment (including both dewatering and stabilization), transportation, and disposal practices. Each of these operations is described in detail in this section.

As can be seen in the table, FGC waste management operations may include (1) initial dewatering in a clarifier/thickener; (2) secondary dewatering with a vacuum filter or centrifuge; (3) stabilization by addition of ash (with dewatering) and/or for commercial additives; (4) pipeline transport to the disposal sites; and (5) disposal into a pond or landfill.

FGD SLUDGE TREATMENT TECHNOLOGY

Dewatering

Dewatering reduces the volume of sludge, removes and recirculates water, and improves sludge handling characteristics. Dewatering processes with demonstrated or potential applicability to scrubber sludges are:

- Clarifiers
- Centrifuges
- Vacuum filters
- Solar evaporation ponds
- Bed dryers
- Thermal dryers

The first four processes listed above have been applied to scrubber sludges, and operating experience is documented. The other processes listed have not been applied to scrubber sludges but have been used successfully for other types of industrial and municipal sewage sludges. The following subsections review applicability of the above dewatering techniques to FGC sludges.

Clarifiers--

Clarifiers (also referred to as settling tanks and gravity thickeners) are a standard unit treatment process on most

TABLE 17. CURRENT FGC WASTE MANAGEMENT PRACTICES IN THE U.S. (JUNE 1977)

Process	No. of Operating Units Industrial	 Utility
Treatment		
Dewatering		
. Clarifier/thickener	6	32
. Vacuum filter	6	10
. Centrifuge		4
Stabilization		
. Commercial	0	6
. Other*	2	5
Transportation		
Pipe	1	35
Truck/rail	6	7
Disposal		
Pond (unlined)	1	6
Pond (lined)	1	22
Landfill	6	8
Mine	0	1

* Either continuous or intermittent codisposal with fly ash and/or bottom ash after mechanical dewatering

With either natural low permeability material or similar "foreign" materials full-scale scrubber sludge treatment installations. They are used to reduce sludge volume prior to disposal, secondary dewatering, or stabilization. In addition, clarifiers sometimes function as mixing or preparation basins for recirculated scrubber feedwater.

Clarifiers are a cost-effective means of dewatering FGD sludge and are used even where further dewatering is done by filtration or centrifugation. Clarification reduces the cost of a second dewatering stage by reducing the volume and increasing the solids content of the sludge.

Clarifier design is based primarily on the settling characteristics of the sludge, which in turn are largely dictated by sludge constituents and particle size. Scrubber sludges, particularly those generated by lime or limestone processes, exhibit fair settling characteristics compared to most solids encountered in the chemical processing industry. Laboratory-scale investigations have shown that dilute slurries of lime/limestone scrubbing effluent have a particle settling rate of 30 cm/hr, with more concentrated suspensions settling more slowly (Ref. 129).

Table 18 displays a cross-section of scrubbing operations and their associated sludge flow. These figures are only examples and are by means standard for the given scrubber configuration. Note that the clarifier underflows are in the range of 1.9 to 7.2 ℓpm/MW, or about .06 to .12 dry metric tons/MWh.

The data base for the design of FGD sludge clarifiers is only now becoming available. Table 19 relates clarifier surface area to type of sludge, as obtained from the literature.

Fly ash alone thickens better than most FGD sludges. The settling rate for flocculated fly ash is about 1.0 M^2/TPD for fine ash from eastern coals; western coal fly ash is coarser and generally settles better. The differences in the settling properties of various FGD sludge solids are typically attributed to differences in crystal morphology. Figure 13, although derived from only six data points, demonstrates the apparent settling superiority of sulfate versus sulfite sludges. The underflow design point for this data is about 22 percent solids, with a coagulant concentration of 1 to 2 ppm. In the underflow, it has generally been found that the higher the sulfate content in the solid phase, the higher the underflow solids concentration -- up to 50 percent solids. Studies by Humenick (Ref. 64) did not demonstrate such a marked dependence of settling rate on percent sulfite oxidation (see Table 16). No explanation for disparity could be found in the literature, although the Humenick study did not incorporate a coagulant, as did the studies referenced by Cornell (Ref. 27).

TABLE 18 *. DEWATERING PERFORMANCE BY SELECTED SCRUBBER SLUDGE TREATMENT SYSTEMS

Scrubber Configuration	To Clarifier ℓpm/MW+	To Clarifier % Solids	Clarifier Underflow ℓpm/MW	Clarifier Underflow % Solids	Filtrate ℓpm/MW	System modeled after:
Two-stage Venturi	23.7	4	1.9	38	--	Duquesne-Phillips (2.0% S coal)
Venturi/spray tower	18.2	8	7.2	18	5.3	TVA-Shawnee (3.4% S coal)
TCA scrubber	15.6	8	3.1	40	--	TVA-Shawnee (3.4% S coal)
FDS absorption tower	151.4	-	2.0	15	--	APS-Cholla (0.5% S coal)

* Ref. 12

+ ℓpm/MW = liters per minute per megawatt

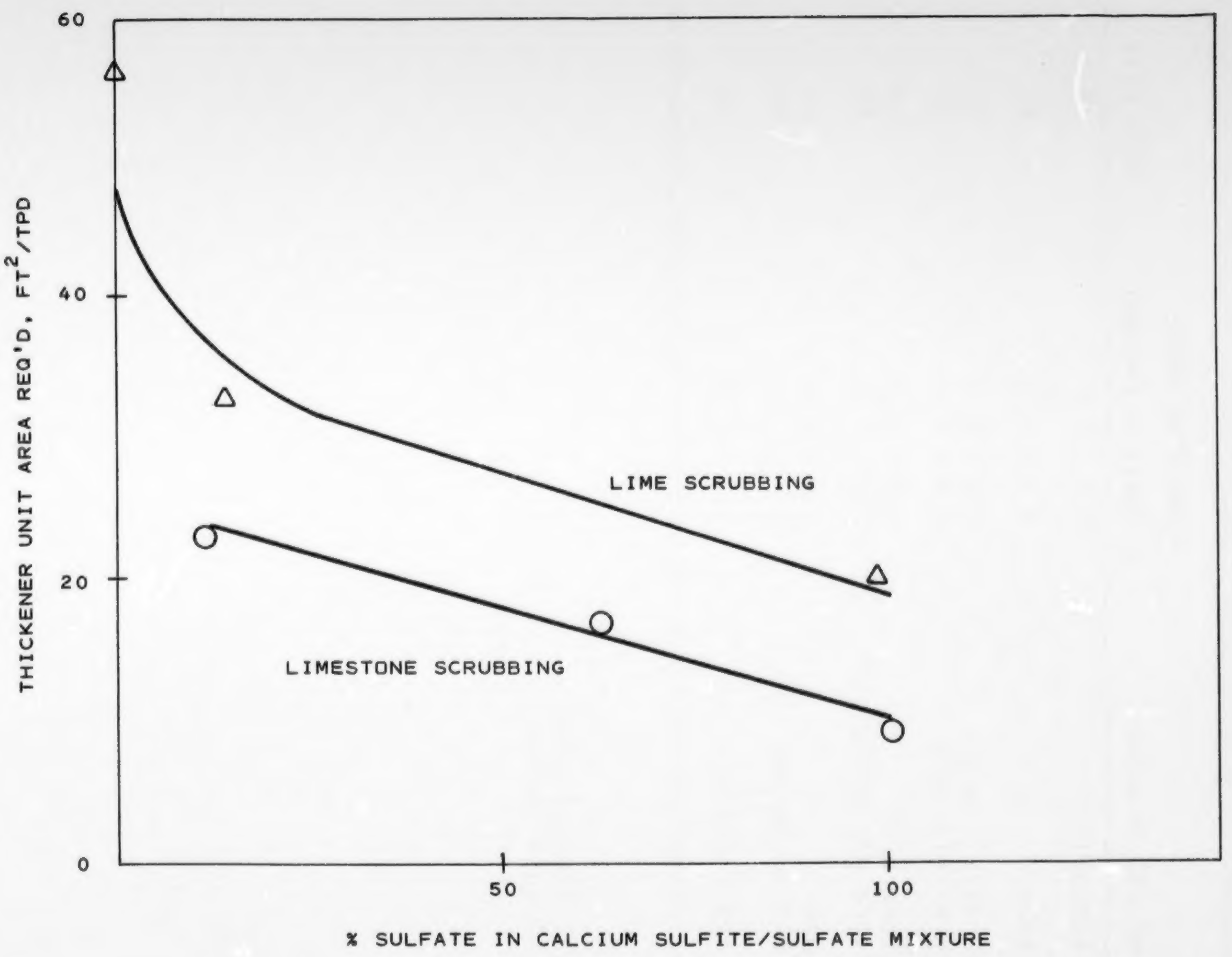

Figure 13*. Thickener sizing vs solid-phase sulfate predominance$^+$.

* Ref. 27
+ All with coagulant use

TABLE 19. CLARIFIER SURFACE AREA REPORTED FOR VARIOUS SLUDGES

Type of FGD Process	Clarifier Area m^2/metric ton/day	Reference
Lime scrubbing	2.0 - 2.5	27
Limestone	0.7 - 2.3	27
Double alkali w/f*	1.0 - 2.5	27
Double alkali wo/f	3.0 - 6.0	27
Limestone w/c+	1.2 - 1.5	60
Limestone w/c w/fly ash	0.8 - 1.2	60
Lime w/f	1.3 - 1.7	64
Lime w/f w/fly ash	1.0	64
Lime and limestone	3.5 - 6.0	64

* With flocculation
+ With coagulation

Reactor-Clarifiers--

Reactor-clarifiers are finding increased application in FGD sludge dewatering, particularly in double alkali systems. These units employ a combination drive to rotate the rake arm at a slow rate and the recirculation pump at a faster rate, resulting in a more thorough mixing than that provided by a conventional clarifier. FGD systems that can best utilize the reactor-clarifier are double alkali systems (which need good mixing for sorbent regeneration) and lime/limestone systems employing a coagulant. A series of reactor-clarifiers, such as those used at the General Motors Parma plant, can also reduce the calcium ion concentration in the double alkali return liquor, thereby reducing scaling in the scrubber.

Centrifuges--

The use of centrifuges for sludge dewatering has had laboratory and pilot scale analysis and widespread use in Japan. Centrifugation is an efficient technique for removing unbound moisture from wetted solids; however, it entails comparatively high power-consumption and maintenance requirements.

Diverse centrifuges are available commercially, which differ primarily in the design of the collection surface and of the feed and discharge mechanisms. Bowl-type centrifuges have been applied to scrubber sludges.

Generally a centrifuge is employed for slurry dewatering when (1) the solids tend to attain a crystalline shape, and when (2) the solids will not cause severe abrasion of the removal screw used in the solid-bowl type centrifuge normally employed for slurry dewatering. Severe abrasion, and consequential high maintenance costs, are endemic to centrifuge applications in FGD sludge treatment. This problem encourages use of a vacuum filter instead of a centrifuge. Also, the shape of calcium sulfite crystals does not lend itself well to centrifuge application (Ref. 27).

Dravo, TVA, and EPA investigated separately the use of centrifuges to dewater scrubber sludges. Dravo, using lime sludge from the Duquesne Light Company's Phillips Station, achieved only moderate dewatering efficiencies using a continuous centrifuge. The TVA results using limestone sludges were better, leaving as little as 37 percent moisture in the centrifuge cake. The use of a centrifuge to dewater sludge from the Chiyoda process (high sulfate/sulfite ratio) resulted in a 10-15 percent moisture cake (Ref. 133).

The Aerospace Corporation study (Ref. 139) analyzed the comparative dewatering properties of sludges with varied sulfate/sulfite ratios. Using clarifier bottoms with equal water contents, it was observed that high sulfate sludge dewatered to less than 35 percent moisture using a lab centrifuge, while the high sulfite sludge was reduced to 44 percent moisture. It was concluded that crystal morphology caused the disparity in results.

Vacuum Filtration--

The vacuum filter process appears to be the best secondary dewatering technique for most FGD sludges. Both the revolving drum and belt filter designs yield better overall performance (when reliability is considered)than the centrifuge. Like other dewatering methods, however, process effectiveness is highly dependent on sludge characteristics and is subject to operating difficulties.

Sludge variables that are known to affect filter performance are concentration and nature of solids, viscosity, temperature, and compressive strength. Operating variables are vacuum strength, filter media, drum speed, degree of drum submergence, and amount of fluid agitation. Problems encountered include cake cracking and difficulties with cake removal from the filter media, both of which resulted in temporary shutdown of experiments.

The filtration rate is partially dependent upon the sulfate/sulfite ratio. Filtration rates for high sulfate limestone sludges are typically between 730 and 1220 kg/hr/m^2 of filter area (Ref. 27).

High sulfite lime scrubbing sludges are reported to filter at rates of 250 to 300 kg/hr/m^2. The optimal filtration rate is a function of the specific sludge and should be determined individually.

Double alkali systems have recorded the most FGD sludge vacuum filtration experience. Double alkali sludge often contains undesirable amounts of purged sodium salts. To alleviate this problem, the cake is usually washed on the filter. The amount wash time required may overshadow the filtration rate itself and should be determined first through laboratory studies. Although double alkali crystals are coarse and filter well, the wash time generally places the overall filtration rate near that of a high sulfite lime system.

EPA investigations at the TVA Shawnee plant showed that a 55 to 70 percent solids filter cake could be achieved, using a flow rate of 2,000 to 2,200 ℓ/hr/m^2 and a feed of unknown sulfate/sulfite ratio. Further investigations by Dravo using a high sulfite sludge yielded a cake with 45 to 55 percent solids (60 percent with cake manipulation). The comparative study done by Aerospace for EPA found that sludges of varying sulfite content filtered equally well (65 percent solids), but that vacuum release caused the sulfite portion to rewater (Ref. 129).

The Louisville Gas and Electric Company's Paddy's Run No. 6 FGD system employs twin rotary drum vacuum filters. Each has a cloth area of 13.9 sq m (150 sq ft) and can handle 11 t/hr of the high sulfite sludge. The input sludges contain 22-24 percent solids, and the filter cake is generally between 35 and 40 percent solids. No precoat is used on the filter. Paddy's Run No. 6 is a peak load unit for LG&E, and the filters are operated intermittently for several months at a time (Ref. 60).

The Gulf Power Scholz #1 double alkali unit has logged over a year of vacuum filtration experience. The filter was constructed of fiberglass instead of stainless steel to avoid chloride corrosion. The following problems have been encountered with this unit:

- Erosion of fiberglass scraper blade, resulting in jagged edges that tear the cloth;
- Erosion of the bridge valve due to solids carried through cloth holes;
- Loss of vacuum due to cracks in the internal drum trunnion tubes;
- Cracking of the plastic caulking strips, allowing retention ropes to loosen and releasing the cloth panels;
- Failure of the fiberglass rocker arm used to agitate the slurry in the filter tub.

The Gulf power unit achieved 50 to 55 percent solids in the cake with 2 to 12 percent soluble solids on a dry cake basis. The sludge is predominantly sulfite containing only 15 to 25 percent sulfate in the sulfur-bearing salts (Ref. 83).

The Caterpillar Corp. plant in Joliet, Illinois, operates two vacuum filters, each capable of handling the total solids load. The filter belts, woven of multifilament polypropylene, had failed frequently due to clogging, until higher pressure spray jets were installed. The system vendor is currently experimenting with other materials and weaves to optimize the operation (Ref. 83).

Another double alkali system, at the GM Chevrolet plant in Parma, Ohio, also employs two vacuum filters. The filter belts were originally made of polypropylene cloth but were changed to nylon to improve cloth release. However, the nylon appears to wear more rapidly due to fly ash abrasion. Modification in the washing system is expected to alleviate this problem (Ref. 52).

Solar Evaporation Ponds--

Use of solar energy to evaporate unbound moisture is the basic principle of sludge ponding. The prerequisites for an effective solar drying pond are (1) a net evaporation/precipitation ratio in excess of unity, and (2) a pond liner or lining soil that minimizes permeation through the pond bottom. Liners available include clay, asphalt, cement, plastic, or synthetic rubber. When protection of the groundwater resource is already sufficient, unlined ponds may be allowed.

Many solar evaporation ponds -- some of which double as clarification/recirculation units -- have been installed throughout the United States for scrubber sludge drying.

In areas of favorable climate, ponding is the most economical means for drying sludge. The mechanics of pond design and operation are discussed in detail later in this section.

Bed Drying--

Dewatering scrubber sludge by solar drying on a bed with porous underdrainage has been investigated to a small extent on the laboratory scale. A bed dryer uses a granular bed for drainage and an open-air space above the bed for surface moisture evaporation. The bed media is graded, with granular size increasing from small sand at the contact surface to large gravel at the bottom adjacent to the drainage ports. Bed thicknesses vary depending on sludge requirements; however, 12-24 in is common for municipal sewage sludges.

Bed drying of scrubber sludges was studied by the Aerospace Corporation using sludges with varied sulfate/sulfite ratios. Using a column simulator, sulfate sludge dewatered to 50 percent solids; sulfite sludge dewatered to only 35 percent solids. Exposure to water caused the drained sludges to rewater readily (Ref. 139). In addition to the rewatering problem, sufficient bed capacity for a full-scale operation would require a very large area.

Thermal Drying--

Thermal drying is a proven dewatering method for municipal sewage sludges, and experiments have been conducted to test its application to scrubber sludge. The types of dryers commonly used are rotary drums and atomizing spray dryers. Most thermal dryers use hot air. The rotary drum configuration passes air through or around the drum, while spray dryers circulate hot flue gas through atomized sludge. Multiple hearth dryers are available in several configurations, including a hollow screw conveyor that transfers the heated air along its axis of rotation while in contact with the sludge.

Koch Engineering has developed an atomizing system for use in conjunction with a limestone or double alkali wet-scrubbing unit. The spent scrubber slurry is atomized into droplets and injected into a low-temperature flue gas stream (149°C); moisture is evaporated in the stream, and the dry powdered solids along with fly ash are collected at the bottom. Dewatering efficiencies in excess of 90 percent have been demonstrated on a pilot scale (Ref. 129).

Thermal drying can conceivably dewater sludge to any moisture content desired; the major drawback is the associated high rate of energy consumption. Unlike sewage sludge, which can be burned to provide drying heat, scrubber solids must depend on other fuel sources or hot flue gases for the drying operation. In areas where other techniques of drying are not practical, or where land is at a premium, thermal drying may be a feasible alternative for sludge dewatering.

Stabilization

General--

Stabilization refers to the addition of fly ash, bottom ash, and/or chemicals to the FGD sludge for the purpose of: (1) improving the load-bearing properties of the disposal sludge and/or (2) decreasing the mass transport rate of contaminants leaching out of the sludge. An increasing number of commercial stabilization processes and services are being offered for FGD sludge treatment. These commercial stabilization processes are sometimes called fixation processes. To avoid confusion, only the term stabilization will be used herein. For additional clarity, commercial stabilization will be used for proprietary processes being marketed, and noncommercial stabilization will indicate nonproprietary stabilization performed by the utilities themselves. By contrast, untreated sludge will refer to FGD sludge that has not been stabilized.

Stabilization techniques employed thus far have incorporated such power plant wastes as fly ash and bottom ash, thereby consolidating several waste disposal activities into one activity. Stabilization can reduce the volume required for disposal through the mechanical dewatering operations included in some systems. Since pozzolanic stabilization improves the load-bearing and handling characteristics of sludge, such materials can be used as a fill material for road base, berms, embankments, and dams (Ref. 76). In addition, stabilized sludge often has less pollution potential than raw sludge. This is because the stabilization process normally restricts the movement of water through the sludge and/or chemically binds the contaminants so they are less readily dissolved by permeating water.

Status of Stabilization Processes--

In June 1977, approximately 11 power plants (see Table 5) will stabilize their FGD sludge under the definition of stabilization used herein. The stabilization operations are categorized as follows:

- Commercial stabilization -- 6 sites
- Noncommercial stabilization, landfill disposal -- 7 sites

Some of the above noncommercial stabilization processes are haphazard in that they are largely a simple codisposal of FGD sludge and ash.

A variety of commercial stabilization processes and services are available for FGD sludge treatment. Several of these services use a proprietary additive or process. IU Conversion Systems (IUCS) offers a patented treatment procedure using the lime-fly ash reaction to produce a structurally stable and low-permeability material. Dravo Lime Co. offers a stabilization service utilizing a proprietary additive, Calcilox^{R}, which after a curing 2-4 weeks will solidify either in a landfill or under water. Both of the above commercial services are under long-term contracts with one or more utilities.

Research into FGD Sludge Stabilization--

Each type of stabilization process results in a material with a different set of physical and chemical properties. Research has been under way for several years to evaluate existing stabilization processes and to develop new processes. Thus far, the most extensive studies of stabilized sludge and its properties have been completed by the Aerospace Corporation for EPA (Ref. 96), the Army Corps of Engineers Waterways Experiment Station for EPA (Ref. 104) and IU Conversion Systems, Inc. (Ref. 158, 165).

A major emphasis has been placed upon the leaching of contaminants from stabilized FGD sludge. Four approaches to simulating sludge leachate generation have been employed thus far:

1. Pressurized flow of small volumes of water or leaching solution through stabilized sludges, with results giving some indication of soluble salts depletion as a function of pore volumes leached (Ref. 96);

2. Surface Washing of stabilized sludge in a packed column, representing rainwater and groundwater washing of the sides of a sludge monolith, such as a stable landfill (Ref. 103);

3. Agitated washing of a sludge plug, representing surface runoff from a stable landfill (Ref. 112);

4. Elutriation of crushed, stabilized sludge, representing the solubility limits of the various sludge contaminants Ref. 96).

Approaches 1 and 4 are representative of convective leaching of stabilized sludge, while 2 and 3 represent diffusion-limited leaching. The latter approaches most closely represent the mechanics of leaching within a stabilized mass.

The Aerospace Corporation (Ref. 96) recently completed a broad-based, ongoing study to determine environmentally sound disposal of solid and liquid wastes produced in FGD processes. The tasks associated with evaluating stabilization of FGD sludges include (1) evaluation of chemical treatment or conditioning techniques needed to achieve environmentally sound disposal; (2) identification and technical evaluation of environmentally sound disposal methods including landfill design and associated costs; and (3) planning and support of an EPA FGD waste-disposal, field-evaluation program.

Studies are being conducted by the U.S. Army Engineer Waterways Experiment Station (WES) in Vicksburg, Mississippi (Ref. 104), to evaluate chemical treatment (stabilization) and environmental effects associated with the disposal of FGC wastes. The program, which also studies a number of industrial wastes, has been divided into three areas encompassing the following tasks:

- Assessment of the pollution potential of the leaching of untreated and chemically fixed FGC wastes;
- Site survey and environmental assessment of existing solid waste disposal sites;
- Evaluation of existing FGC waste fixation technology.

Table 20 display the stabilization processes used by WES in this investigation.

IUCS has performed an extensive in-house evaluation of FGD sludge properties after stabilization by their proprietary "Poz-O-Tec" process. IUCS is currently under contract with five utilities to provide stabilization and disposal services for FGD sludge and fly ash. Both physical and chemical

TABLE 20.* DESCRIPTION OF PROCESSES USED BY WES TO STABILIZE FGD SLUDGE SAMPLES+

1. Stabilization Processes

Code Letter	Description
A	Fly ash and lime mixed to produce pozzolan product+
B	Two additives mixed with sludge to produce soil-like material; hardness is a function of mix proportions*
C	Organic resin* mixed with other additives and sludge to produce rubber-like material
D	Encapsulation of a sludge-resin mixture with .25-in plastic jacket
E	Two readily available additives used with sludge to produce concrete-like mixture
F	Additive+ mixed with sludge at optimum pH, cured 30 days with supernatant
G	Sludge mixed with waste product of a certain manufacturing process and pH adjusted using a second waste product

2. Sludge Samples Used in Study

Sludge 100 = FGD, lime process, eastern coal
Sludge 200 = Electroplating
Sludge 300 = Nickel/cadmium battery
Sludge 400 = FGD, limestone process, eastern coal
Sludge 500 = FGD, double alkali process, eastern coal
Sludge 600 = FGD, limestone process, western coal
Sludge 700 = Inorganic pigment
Sludge 800 = Chlorine production, brine sludge
Sludge 900 = Calcium fluoride
Sludge 1000 = FGD, double alkali, western coal

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* Ref 104

+ Patented or proprietary

properties of the pozzolan-type stabilization product have been studied. These properties include (Ref. 147).

Physical	Chemical
Density	48 hour shake test
Compression strength	Runoff test
Permeability	Chemical analysis
Reslurrying tendency	Crystal morphology

As the disposal of the Poz-O-Tec product is a landfill operation, leaching tests by IUCS have concentrated on simulating runoff conditions.

Physical Properties of Stabilized Materials--

The previously mentioned studies have evaluated such physical characteristics as permeability, compressive strength/compressibility, bulk density, and porosity. Their findings are summarized below.

Permeability--The permeability of stabilized FGD sludge has been investigated in all of the previously mentioned studies. Both commercial and noncommercial stabilization processes were used to prepare samples. Differences between study approaches consisted primarily of emphasis on either in-place permeability or disturbed/pulverized/compacted sludge permeability. In-place (also "undisturbed") permeability is valuable to the pozzolanic types of stabilization, ordinarily the product of which would not be remolded. Compacted permeability would be valuable to a landfill disposal operation for soil-like stabilization products, where landscaping or compaction is important.

Sludge permeability along with rate and degree of saturation and hydraulic head, determines the rate of contaminant transport from the site to the surrounding environment. When the site has a relatively high permeability, the sludge is saturated, and there exists some standing water on the sludge, the sludge may require treatment in order to serve as the rate limiting step for mass transport. The actual degree of permeability decrease due to stabilization has therefore been a major research subject. The permeability of untreated sludge is discussed in Section 6.

The Aerospace results suggest that the commercial processes tested decrease sludge permeability by as much as a factor of a thousand. The permeability coefficients for raw sludge were 7×10^{-4} cm/sec to 1×10^{-5} cm/sec; coefficients for treated sludges were 7×10^{-4} cm/sec to 4×10^{-5} cm/sec for remolded samples, and 5×10^{-5} cm/sec to 5×10^{-8} cm/sec for undisturbed samples. However, the small samples tested does not provide statistically conclusive proof of the exact magnitude of this decrease in permeability.

The results of the Aerospace permeability evaluation are shown in Table 21. The Chemfix process used in the study is a proprietary stabilization process, producing a soil-like material from the reaction of the sludge with soluble silicates and silicate setting agents. The pulverized samples were packed into columns to simulate landscaping or remolding, while the undisturbed samples represented cores taken from the TVA Shawnee experimental site. Except under unusual circumstances, an FGD disposal site would be undisturbed and would reflect undisturbed permeabilities.

The permeabilities of the WES materials were in close agreement with the Aerospace results. Untreated compacted sludges demonstrated permeability coefficients ranging from 6.04 x 10^{-5} cm/sec to 1.07 x 10^{-5} cm/sec. Only processes A and E decreased the permeability by more than two orders of magnitude.

Commonwealth Edison studies (Ref. 96) of treated sludge permeability indicated a much lower in-place permeability than the WES and Aerospace results using noncommercial processes. These studies demonstrated permeability coefficients of 10^{-7} cm/sec and less for undisturbed samples. Again, permeability alone does not dictate the mass transport rate; degree of sludge saturation, hydraulic gradient, and complexing effects of the matrix must also be considered.

The important primary conclusion that can be drawn from the results of the three major studies is that the pozzolan type of stabilization processes substantially reduce sludge permeability over that of untreated sludge and soil-like products when not disturbed.

Compressive Strength--

Stabilization, by definition, improves the structural stability of raw FGD sludges. All commercial stabilization processes improve the compressive strength of sulfite sludges. Only pozzolan-type stabilization processes appear to improve sulfate sludge compressive strength.

The Commonwealth Edison study (Ref. 52) evaluated the compressive strength of over 270 test samples. The samples were cured at various temperatures and stabilized with an assortment of admixtures. It was concluded from these data that lime-fly ash and Portland cement-fly ash admixtures gave the most satisfactory results. It was also concluded that low temperatures (22°F) significantly delayed hardening for the mixtures tested.

TABLE 21.* PERMEABILITY OF RAW+ AND COMMERCIALLY STABILIZED FGD

Sample Source	Sample Treatment	Condition	Fractional Void Volume	Permeability Coefficient, cm/sec
Shawnee limestone	Untreated	. Column packed as slurry	0.58	$8.5\text{x}10^{-5} - 2.3\text{x}10^{-4}$
		. Compacted wet	0.55	$5.9\text{x}10^{-5}$
	IUCS	. Pulverized++	0.69	$2.2\text{x}10^{-4}$
		. Solid, undisturbed	0.54	$5.5\text{x}10^{-8}$
	Dravo	. Pulverized++	0.78	$3.2\text{x}10^{-4}$
		. Solid, undisturbed	0.75	$6.9\text{x}10^{-5}$
	Chemfix	. Pulverized++	0.68-0.70	$4.1\text{-}4.7\text{x}10^{-5}$
		. Solid, undisturbed	0.72	$1.5\text{-}2.1\text{x}10^{-5}$
Shawnee lime	Untreated	. Compacted wet	0.72-0.75	$8.1\text{x}10^{-5}\text{-}2.5\text{x}10^{-4}$
	IUCS	. Solid, undisturbed	0.57	$5.5\text{x}10^{-5}$, $5.5\text{x}10^{-7}$
Mohave	Raw	. Column packed as slurry	0.34-0.47	$1.6\text{-}7.5\text{x}10^{-4}$
	IUCS	. Pulverized++	0.55-0.65	$7.9\text{x}10^{-5}\text{-}7.4\text{x}10^{-4}$
		. Pulverized, compacted wet++	0.53	$1.9\text{x}10^{-4}$
Duquesne	Untreated		0.49-0.68	$7.4\text{x}10^{-5}\text{-}1.3\text{x}10^{-4}$
	Dravo	. Pulverized+	0.70-0.78	$3.8\text{-}4.9\text{x}10^{-4}$
		. Pulverized, compacted wet++	0.76	$2.1\text{x}10^{-4}$

* Ref. 96

+ Shawnee samples collected with fly ash

++ For test purposes only; does not reflect actual disposal conditions

The WES studies found the solidified material (processes A, F, and G) to exhibit unconfined compressive strengths of 70 to 350 N/cm^2 (100 to 500 lbs/in^2). Sludge treated with process E to demonstrated strengths of nearly 3,500 N/cm^2 (5,000 lb/in^2). Process B material, with strengths ranging from 14 to 350 N/cm^2 (20-50 lb/in^2), was only slightly greater in strength than untreated sludges. Compaction tests performed on process B materials indicated that field compaction of certain fixed sludges might create some difficulties. Several samples actually decreased in density after compaction, while others showed no change.

Studies performed by Ontario Hydro (Ref. 96) at their Lakeview test facility evaluated the compactibility of sludge stabilization admixtures. Table 22 describes the mix consistency and compactibility for various proportions of admixture. Mixtures that exhibited the greatest compactibility contained a high percentage of fly ash combined with small amounts of lime or cement.

The EPA Shawnee Field Evaluation (Ref. 140) tested the IUCS, Chemfix, and Dravo stabilized FGD sludges for wet and dry compaction strength. The IUCS material consistently demonstrated unconfined compressive strengths in excess of 280 N/cm^2 (400 lb/in^2), while the other two processes (oven-dried samples) never exceeded 114 N/cm^2 (163 lb/in^2) and 32 N/cm^2 (45 lb/in^2), respectively.

Bulk Density--The change in FGD sludge bulk density as a result of stabilization has also been studied, but not to the same extent as permeability and strength. The WES investigations observed bulk densities of 0.8 to 1.7 g/cm^3 for five treatments used; the specific densities for each sludge and process are shown in Table 23. With the exception of process G, stabilization increased the bulk density of raw sludges.

Results from the EPA field evaluation showed a lower range of bulk densities for commercially stabilized sludges. The dry densities ranged from a high of 1.08 g/cm^3 for the IUCS solid mass to a low of .59 g/cm^3 for the Dravo material (underwater). The difference between the WES and Aerospace studies is due to the use of remolded samples by Aerospace and as-cast samples by WES.

It can be concluded from these results that pozzolanic processes produce a higher density material than other admixtures or processes producing a soil-like product. The latter would therefore be expected to consolidate more under load, as in a landfill operation or reclamation of the disposal site.

TABLE 22.* MIX CONSISTENCIES WITH VARIOUS ADDITIVES FOR LAKEVIEW GAS SCRUBBER SLUDGE CONTAINING 65 PERCENT SOLIDS

Mix Proportions	Consistency of Mix	Remarks on Compactability
Sludge + 5% Lime Sludge + 10% Lime Sludge + 5% Cement Sludge + 10% Cement	Soft and wet	Both lime mixes were too wet to compact, even after 1 week of retention. The cement mixes were too wet to compact initially but were compactable after 24 hours.
Sludge + 15% Cement Sludge + 52% Fly Ash Sludge + 39% Fly Ash + 5% Cement Sludge + 39% Fly Ash + 15% Cement	Firm and wet	All mixes were too wet, although some only slightly, causing some slumping of specimens after removal from mold
Sludge + 65% Fly Ash Sludge + 15% lime Sludge + 39% Fly Ash + 5% Lime Sludge + 65% Fly Ash + 5% Cement Sludge + 65% Fly Ash + 15% Cement	Firm and moist	Ideal mix combinations for compaction
Sludge + 65% Fly Ash + 5% Lime	Firm and dry	Slightly drier than above mixes, but compactable
Sludge + 39% Fly Ash + 15% Lime Sludge + 65% Fly Ash + 15% Lime	Powdery and dry	Too dry and powdery for proper compaction

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* Ref. 96

TABLE 23.* EFFECT OF TREATMENT ON BULK DENSITY

		Bulk Density (g/cm^3)					
Location	Process	Untreated	Process A	Process B	Process E	Process F	Process G
Eastern	Lime	0.83	1.60	1.23	1.62		
Eastern	Limestone	1.01	1.73	1.42	1.32		1.00
Eastern	Double alkali	0.84	1.53	1.45	1.59		0.84
Western	Limestone	1.42	1.75	1.27	1.77	1.30	0.91
Western	Double alkali	0.76	1.55	1.30	1.32		1.01

* Ref. 104
+ Refer to Table VII-5 for code

Particle Size--Data on the particle size distribution of treated sludge is important when describing physical behavior, particularly properties such as permeability and bulk density. This is expecially important for the soil-like materials, as the solid pozzolans behave as a constant mass and are not intended for remolding.

A comparison of particle size distributions in raw sludge and in soil-like stabilized products (such as Chemfix) was performed as part of the WES effort. Sludge stabilized by process B proved to be much like raw sludge in texture and was given a similar U.S.D.A. classification of loam or fine sandy loam. The particle size distribution remained approximately the same as that of raw sludge, although both finer and coarser gradations were observed for certain sludge types (Ref. 104). These soil-like products can therefore be expected to behave much like sandy loam in their bulk density, permeability, and compressibility.

The particle size distribution of solid stabilized sludge (pozzolanic or other cementitious products) is not important except as it affects the void ratio of the matrix.

Chemical Properties of Stabilized Materials--

Stabilization, as well as providing a structurally improved product, may also reduce the rate of mass transport leaching of soluble contaminants from the FGD sludge. This can be accomplished through a reduction in permeability/porosity and through chemical bonding of contaminants within the stabilized matrix.

Several of the previously named studies have been involved in characterizing the leachate from stabilized sludge. Some of these findings, as they relate to existing water quality standards, are discussed in Section VIII under "Health Considerations." The principal difficulty in evaluating the study results has been to properly assess the applicability of the various leaching tests being used. The following is a summary of the results compiled to date.

Leaching experiments conducted by Aerospace examined leachate from treated FGD wastes under both aerobic and anaerobic conditions. Two sets of leaching experiments were conducted. In the first set, three laboratory columns were packed with process wastes obtained from the TVA Shawnee limestone, the Arizona Cholla limestone, the Duquesne Phillips lime, the GM Parma double alkali, and the Southern California Edison Mohave limestone scrubbing systems. The chemically treated sludge was dried and pulverized before it was packed into the leaching column, for the purpose of maximizing surface contact area to obtain an indication of potentially available contaminants.

Leaching water (unbuffered) adjusted to pH 4, 7, and 9, with either HCl or NaOH, was used in each set of columns. The leaching water and the leachate were allowed to react with air in order to stimulate aerobic conditions. A second set of leaching experiments was conducted under anaerobic conditions. These experiments duplicated the first experiments except that the leaching water and leachate were protected from interaction with the atmosphere. Also, leaching water with a pH 7 was used, because no discernible effect had been noted in the aerobic columns as a result of differences in the initial pH of the leaching waters.

The Shawnee FGD Waste Disposal Field Evaluation (Ref. 96, 141) was initiated to evaluate and monitor the field-site disposal of untreated and treated FGC wastes. Its purpose is to determine the effects of several scrubbing operations, waste treatment methods, disposal techniques, soil interactions, and field operation procedures. Test samples of treated and untreated wastes, groundwater, standing water, leachate (both ground and surface), and soil cores are being analyzed in order to evaluate the environmental acceptability of current disposal technology.

The disposal evaluation site consists of five disposal ponds, each occupying approximately 0.1 ac near the TVA Shawnee Power Station at Paducah, Kentucky, approximately 1 mi south of the Ohio River. All the ponds were filled between October 7, 1974 and April 23, 1975 to a depth of about 3 ft. Two of the ponds contain untreated wastes; each of the remaining ponds contains wastes chemically treated by one of the three commercial contractors.

The Chemfix-treated material was fractured and contoured by a backhoe; the Dravo-treated material represents curing and disposal under water where high strength is not necessarily required; and the IUCS-treated material was not compacted by placement vehicles that would be used in a full-scale operation. Therefore, comparisons between processes are neither attempted nor implied in the evaluations for the purpose of this document.

Within each pond is a leachate well for sampling water that collects at the waste-soil interface. A groundwater well is located on a berm of each pond, between the sludge and the river. Groundwater wells are located approximately 100 ft south of each pond (away from the river) to provide for the monitoring of background water quality. The disposal sites are also being monitored periodically for leachate, supernate, and groundwater quality; soil chemistry changes; and treated waste chemical and physical qualities.

The laboratory studies by Aerospace revealed a similarity in leaching profiles between untreated sludges and stabilized (both pulverized and undisturbed) sludges. The principal differences are in (1) the lower concentrations of TDS and major chemical species in treated sludge leachate, and (2) the more gradual decrease in concentration observed for treated sludge leachate contaminants. Aerospace tests included elutriation of pulverized pozzolanic stabilized sludge as a worse case, which is not indicative of actual field conditions. The decrease in surface area contacted through a stabilized sludge matrix will result in a decreased rate of mass transport.

In the leaching of untreated waste, a higher rate of decrease in concentration was observed under anaerobic conditions. In assessing the results obtained from the leaching of commercially stabilized wastes, it was concluded that the type of conditions -- i.e., aerobic vs. anaerobic -- would not be a significant factor in the selection of a particular chemical treatment process.

Based on the results, Aerospace concluded that chemical treatment generally improves leachate quality. The degree of improvement is dependent on the specific waste and the specific chemical process used. The concentration of the major chemical species in the leachate from the chemically treated waste was observed to be approximately 1/4 to 1/2 the concentration in the leachate from untreated waste. When the results are examined for effect on trace metals, it was not concluded that chemical treatment of FGD waste improved the leachate quality (Ref. 96).

Another significant result of the Aerospace investigation concerns the comparative rates of decrease in concentration for the various leachate components. Figures 14 and 15 demonstrate this relationship for untreated and Chemfix stabilized sludges under anaerobic conditions. Actual data extend through 30 to 50 pore volumes of pulverized sludge. These data seem to indicate that TDS, Pb, and SO_4 concentrations represent the minimum rate of decrease among contaminants examined. Once initial concentrations of the contaminants are known for a given sludge, one or more of these three species would serve as a worst case indicator of leachate quality. Again, results obtained for trace metals other than those shown were too dispersed to draw similar conclusions. Table 24 compares the composition of leachate constituents for both raw sludge and Chemfix treated sludge. Of the contaminants shown, only Cu achieved a slower rate of decrease in concentration than TDS. The primary value of this data is to identify one or more tracer ions which can serve as monitoring parameters to indicate pollutant migration from FGD sludge disposal sites.

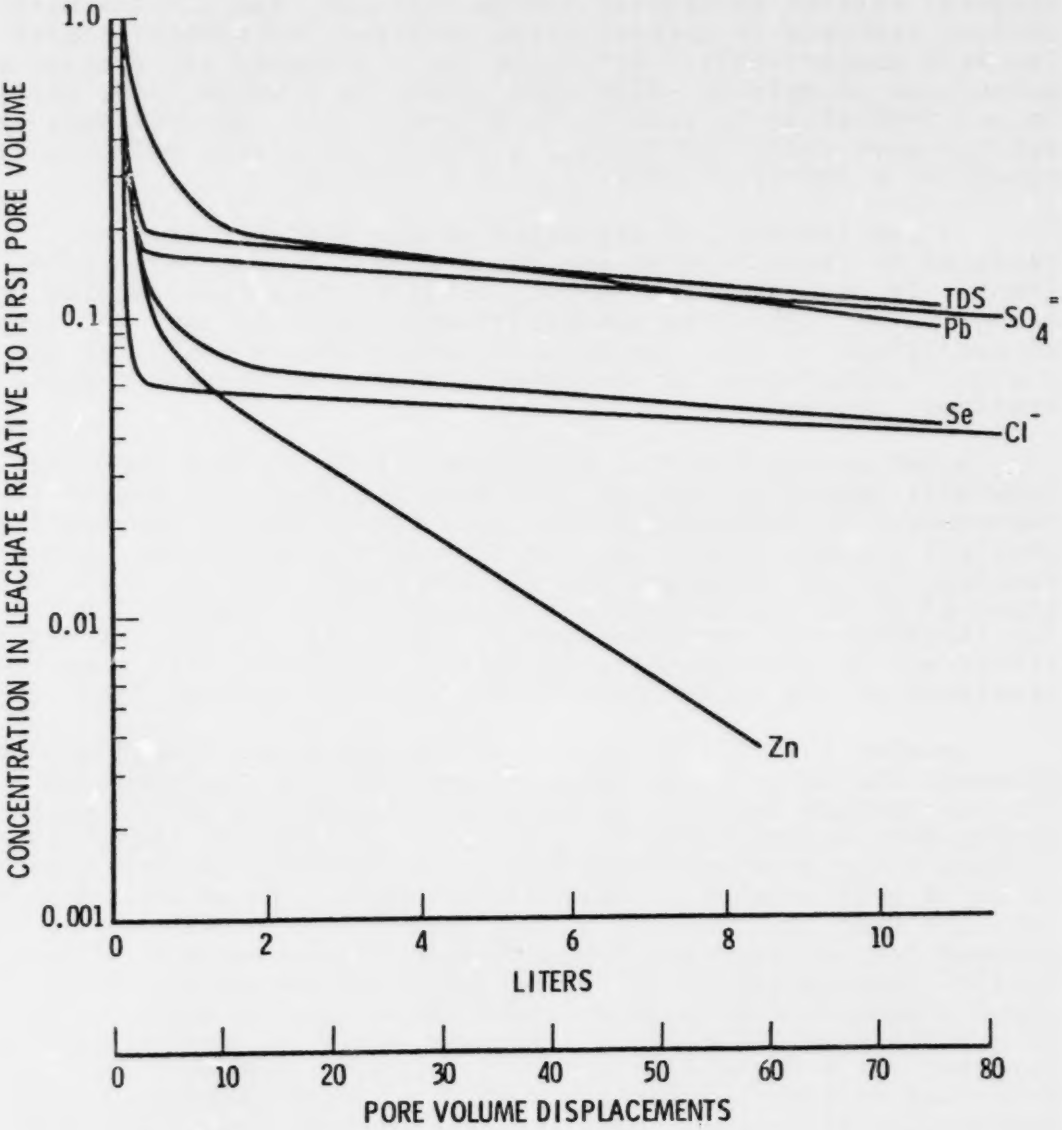

Figure 14. Leachate analyses from EPA/TVA Shawnee untreated limestone waste: anaerobic conditions.

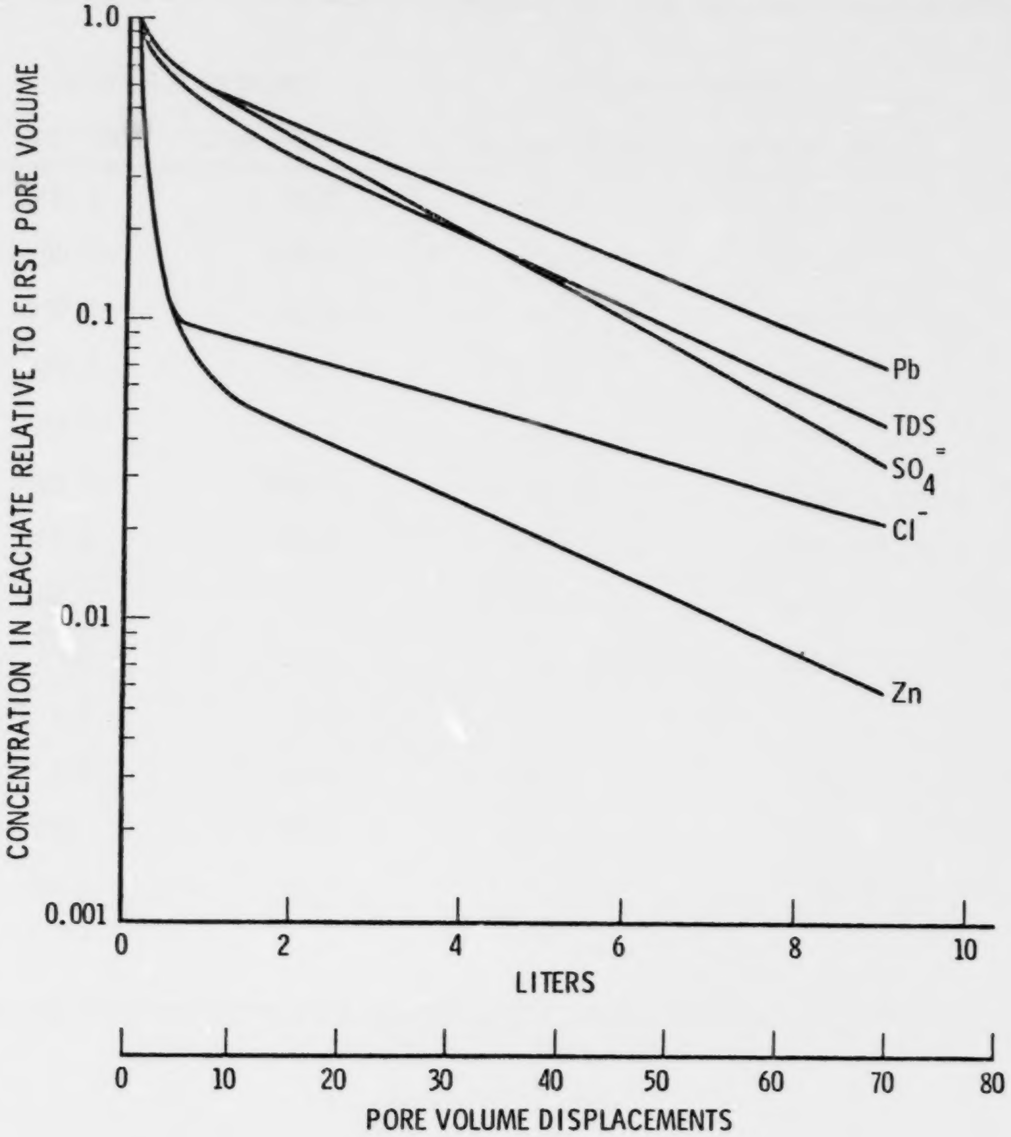

Figure 15. Leachate analyses from EPA/TVA Shawnee treated limestone waste (Chemfix): anaerobic conditions.

TABLE 24.* COMPARISON OF THE LEACHATE CONSTITUENTS FROM EASTERN LIMESTONE SLUDGE AND CHEMFIX TREATED SLUDGE

	Sludge - Aerobic		Chemfix - Aerobic	
	1st Pore Vol.	50th Pore Vol.	1st Pore Vol.	50th Pore Vol.
As	0.14	0.01	0.04	0.006
Cd	0.003	<0.001	0.003	<0.001
Cr	0.09	0.003	0.04	<0.001
Cu	0.01	0.010	0.05	0.005
Pb	0.25	0.01	0.35	<0.001
Hg	<0.05	<0.00005	<0.005	<0.0005
Se	0.08	0.006	0.01	0.002
Zn	0.20	0.045	0.5	0.065
Cl	2300	120	1400	60
F	6.2	<0.2	0.9	0.2
SO_4	10,000	1200	3000	650
TDS	15,000	2400	7000	1500
pH	8.3	5.0	4.70	6.01

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* Ref. 96

Laboratory leaching studies for treated sludge samples from Shawnee showed that the TDS concentration decreased rapidly during the first five pore volume displacements in Chemfix treated sludge. After that, the TDS concentration appeared to be controlled by the solubility of major contaminants such as sulfate, sulfite, and chloride. These data were then applied to five hypothetical case studies and extrapolated in terms of yearly mass loading to site subsoil. The results are shown in Table 25 and Figure 16. This information demonstrates the advantages of low sludge site permeability and limited water percolation through the sludge, in terms of mass transport from the disposal site.

WES has been performing leaching column studies (Ref. 104) for 162 samples of untreated and stabilized sludge since January 1975. The molded sludge cylinders are placed in polypropylene pellets. The fluid velocity down the sides of the cylinder is maintained at about 10^{-5} cm/sec. This configuration simulates (1) groundwater flow along the bottom and sides of a landfill, and (2) flow through a crack in the material as placed. Under these conditions, the leachate quality for treated and untreated sludge would be expected to be similar for the initial wash. Once diffusion, and not solubility, becomes limiting, the leachate from the solid mass would improve in quality. However, the time required to achieve diffusion-limited mass transport is approximately 10 years.

In assessing the pollution potential of the wastes, seven chemical fixation processes were used to treat the selected wastes (Table 20). The processes are being evaluated by means of leaching column studies as well as physical and chemical testing of untreated and fixed wastes.

Analysis of leachate pH by sludge category and stabilization process is being performed by WES. Figure 17 demonstrates the change in leachate pH due to the various stabilization processes. In general, raw sludges with a slightly basic leachate pH were subject to an increase in pH due to stabilization. This concept for the metals that are less mobile at a high pH due to formation of insoluble hydroxides. The effect of stabilization upon leachates is more complex than stated above, but the pH effect is one that could be documented by observed data. The stability of pH is important because of its impact on the longevity of the contaminant immobilization. WES data indicate that the pH of leachates from several stabilized materials was initially higher than that of untreated sludge but is tending to converge with time.

TABLE 25.* CASE STUDIES FOR CALCULATING MASS LOADING OF LEACHATE CONSTITUENTS INTO SUBSOIL

				FGC Waste, Five-Year Fill		
Case	Disposal Method	Surface Water	Waste Condition	Depth ft	Permeability cm/sec+	Fractional Pore Volume
1	Lake#	Constant supernate	Untreated	30	10^{-4}	0.67
2	Lake#	Constant supernate	Treated	30	10^{-5}	0.67
3	Pond	10 in/yr recharge	Untreated	30	10^{-4}	0.67
4	Pond	10 in/yr recharge	Treated	30	10^{-5}	0.67
5	Landfill	1 in/yr recharge	Treated	30	10^{-5}	0.67

* Ref. 96

+ For all cases, subsoil permeability = 10^{-5} cm/sec

# Assumed maximum hydraulic head of 6 ft during filling, including depth of wastes; 1 ft constant water cover thereafter

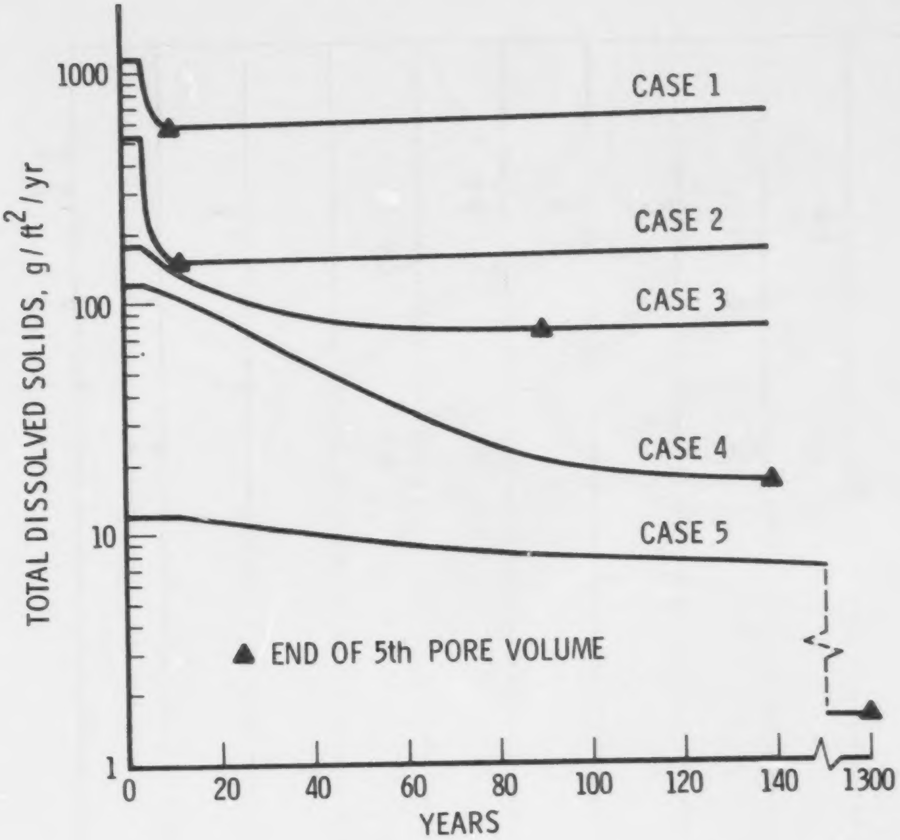

Figure 16.* Projected mass loading of TDS to subsoil for various disposal modes of treated and untreated FGC wastes, based on theoretical considerations.

* Ref. 96

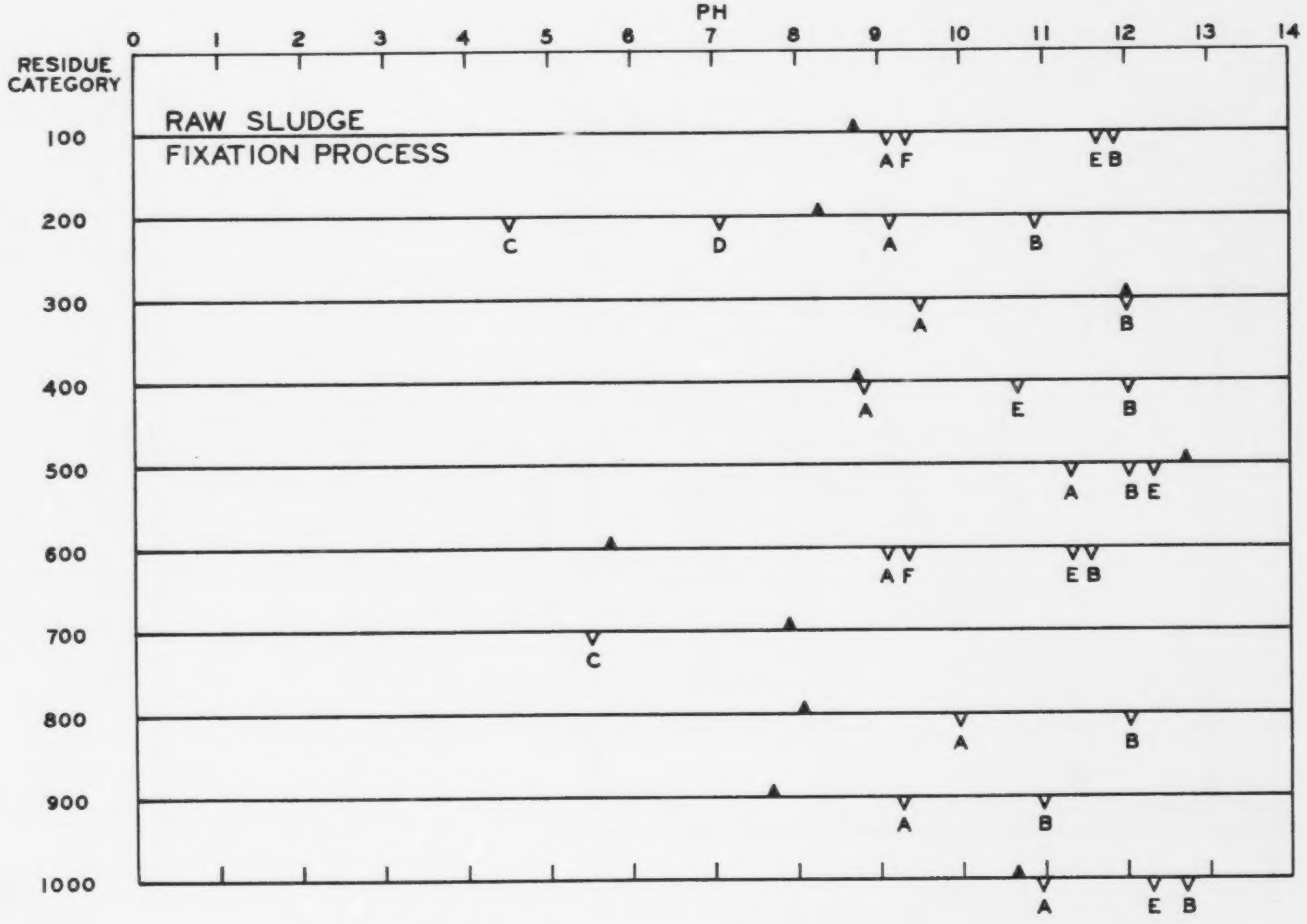

Figure 17. Leachate pH for untreated and treated residues.

The conductivity of the leachates from untreated and stabilized sludge samples was used as an indicator of dissolved solids concentration. The conductivities for untreated sludges were highly variable but were classified as "stable" for six samples and as "decreasing with time" for the other four. The conductivities for stabilized sludges, on the other hand, were all generally decreasing, indicating a decreasing availability of soluble material. Conductivities for six of the samples tested were similar for treated and untreated sludge.

To analyze the effect of experimental design upon leachate behavior, the data from a selected residue, 100, were subjected to an analysis of variance. The design used included all replicates for six time periods, two leaching solutions, and four sludge treatments (one raw and three fixed). The results of the analysis for pH indicated that residue, treatment, time, and several interactions were significant sources of pH variance. It was also noted that variation in leaching solution pH from pH 4.7-7.7 had no effect on the resulting leachate pH. Since most of the untreated and fixed residues demonstrate a strong buffering capacity, the effect of pH in the leaching solution upon column effluent is small and would support the practice of leach testing with one solution. A wider range of solution pH might increase the significance of this effect.

A similar analysis for conductivity showed that treatment, time, and treatment-time interaction effects are significant. This indicates that stabilization indeed affects the conductivity of the leachate, and the effect is a function of time. Again, leaching solution pH was not shown to be a significant factor in determining leachate conductivity.

Analyses for sulfate and copper concentrations were also included in the WES leachate characterization. Data indicate that stabilization is effective at retarding sulfate leaching. Leaching from the stabilized sludges was characterized by an initially high sulfate concentration followed by a rapid decrease in concentration, indicating early leaching of the more soluble forms of sulfate. Few generalizations can be made about copper leaching. All stabilized sludges leached copper to some extent, several producing higher concentrations than the associated raw sludge leachate. Several stabilized sludges actually showed increased copper leach rates with time, a fact that was correlated with the simultaneous decrease in pH. Definite trends could not be identified at the time of the initial report.

In general, it was concluded from the WES data generated thus far that the leaching and performance of fixed FGD sludges is strongly dependent on the type of scrubber and, for the limestone scrubbers, is dependent on the source of coal (initial sulfur content). The double alkali scrubbers tend to produce more soluble sulfate compounds, and thus their leaching behavior is affected by fixation to a greater degree. IUCS data (Ref. 147) indicate that the TDS concentration in untreated double alkali sludge runoff can be reduced by more than 60 percent by Poz-O-Tec stabilization. The limestone scrubbers produce less soluble sulfate compounds, and fixation of these sludges affects the leaching of sulfate to a lesser degree. Within the limestone scrubber sludges, the amount of sulfate available appears to be proportional to the initial sulfur content of the coal utilized (Ref. 104). It was also shown that leachate quality improvement from stabilization was more pronounced for double alkali sludges than for lime/limestone sludges. This improvement is due to the higher solubility of certain double alkali waste products. WES and IUCS results have shown that contaminant transport from stabilized sludge occurs primarily during rainwater runoff, and could remain solubility-limited if disposed of in a properly managed landfill.

Commonwealth Edison (Ref. 96) studied several samples of sludge stabilized using different proportions of admixture. The results are not reported here, as the elutriation test used is not representative of actual field conditions.

IUCS used a variety of leaching tests for stabilized FGD sludge. These include shake tests, runoff tests, permeability tests, and diffusion tests (Ref. 158).

In the shake test, a material with known weight and surface area is placed in contact with a specified amount of deionized water. The water and material are contacted in a shake apparatus for 48 hours. The water is removed for analysis, and the material is exposed to fresh water. That process is repeated for a total of 5 shakes. Each sample of water is analyzed for total dissolved solids, with full chemical analysis and heavy metal analysis on the first and fifth wash.

In the runoff test, a fresh sample of material is placed into a box, the bottom of which is covered with graded aggregate to the depth of approximately one inch. The surface of the material to be tested is exposed to various degrees of simulated rainfall for any amount of time one may desire. Runoff is collected and analyzed. The amount of water absorption per each simulated rainfall may be measured by weighing the box before and after water contact. Permeate which results from the water contact with the surface of the material is collected from the bottom of the box and subsequently analyzed.

The results of a typical shake test for Poz-O-Tec are shown in Table 26. These results, from five consecutive 48 hour washes, indicate that an apparent equilibrium situation for TDS is reached after the third wash. Leaching would then become diffusion limited. The observed range of .01-.05 grams of leachable material/in^2 of sludge surface exposed is important

TABLE 26.* POZ-O-TEC LEACHATE FROM SUCCESSIVE SHAKE TESTS

TDS (ppm)	Grams Leached	Grams/ in^2
974	1.948	.046
338	.676	.015
268	.536	.012
194	.388	.009
214	.428	.010

Surface area: 42.4 in^2
Dilution ratio (in^2/L): 21.2:1

*Ref. 158

in a landfill situation. It indicates that the leachable material is an insignificant fraction of the total available soluble material originally contained in the untreated sludge.

Several unstabilized and stabilized mixes were subjected to runoff tests at various curing periods up to 28 days. Tests were run simulating 2 in rainfall per hour. The runoff water from each test was collected and analyzed. Any water permeating through a test pad during the experiment was also collected and analyzed. Table 27 summarizes such data for two unstabilized mixes and two stabilized Poz-O-Tec materials. Runoff water from Poz-O-Tec materials show lower TDS and TSS contents. TDS typically start at about 2,000 ppm and diminish concentrations to between 50 ppm and 600 ppm after several washings (Ref. 147).

Runoff and shake tests were performed using the Poz-O-Tec product from the EPA Shawnee field study landfill. The results of the shake tests are shown in Figure 18, using both solid and broken cores. It is evident from this figure that diffusion-limited leaching occurred within three to five washings for both samples, but the surface washing phase was completed sooner for the broken piece due to the higher surface area (Ref. 158).

Further work is required before conclusions can be drawn from the sludge leaching data base established thus far in these and other studies. The WES and Aerospace studies indicate at this stage that TDS concentrations in the sludge leachate are initially lower than concentrations in raw sludge and tend to decrease with time. Similar conclusions have been drawn regarding the major dissolved components such as sulfate.

It has also been concluded from IUCS research that a properly managed stabilized sludge landfill (limited contact with groundwater or rainfall) will limit leaching to a slow surface washing mechanism. Uncontrolled contact with water would increase the leach rate until diffusion or permeation (assuming saturation of the mass) becomes controlling.

Combining Waste Streams

It can be advantageous to dispose of FGD sludge with other liquid and solid wastes generated at a power plant. Combinations that are being used or studied include:

- Sludge and fly ash and/or bottom ash
- Sludge and mine tailings or overburden
- Sludge and acid mine effluent (drainage)

FGD Sludge Combined with Fly Ash and/or Bottom Ash--

FGD sludge combined with fly ash and/or bottom ash is the most widely used method of combined waste disposal. Currently,

TABLE 27.* RUNOFF TEST DATA ON STABILIZED AND UNSTABILIZED MATERIALS

		Runoff Water Analysis			Permeate Water Analysis		
Placement Pad	Age	pH	TDS (ppm)	TSS (ppm)	pH	TDS (ppm)	TSS (ppm)
Sludge No. 2 filtercake and fly ash mix	Immediate	7.7	2402	75,824	------------	No permeate	------------
	7 days	7.6	2296	123,190	7.8	4040	868
	28 days	8.3	1800	17,131	7.6	2560	5428
Sludge No. 2 Poz-O-Tec	Immediate	10.8	2240	29,936	------------	No permeate	------------
	7 days	8.8	508	1,299	------------	No permeate	------------
	28 days	8.2	439	709	------------	No permeate	------------
Sludge No. 4 (double alkali) filtercake and fly ash mix	Immediate	10.5	1392	436	------------	No permeate	------------
	7 days	9.2	1664	567	10.9	8364	308
	28 days	9.0	2902	7,643	11.2	24,278	175
Sludge No. 4 Poz-O-Tec	Immediate	11.6	1146	107	------------	No permeate	------------
	7 days	9.6	1010	1,198	------------	No permeate	------------
	28 days	9.1	1180	900	------------	No permeate	------------

*Ref. 147

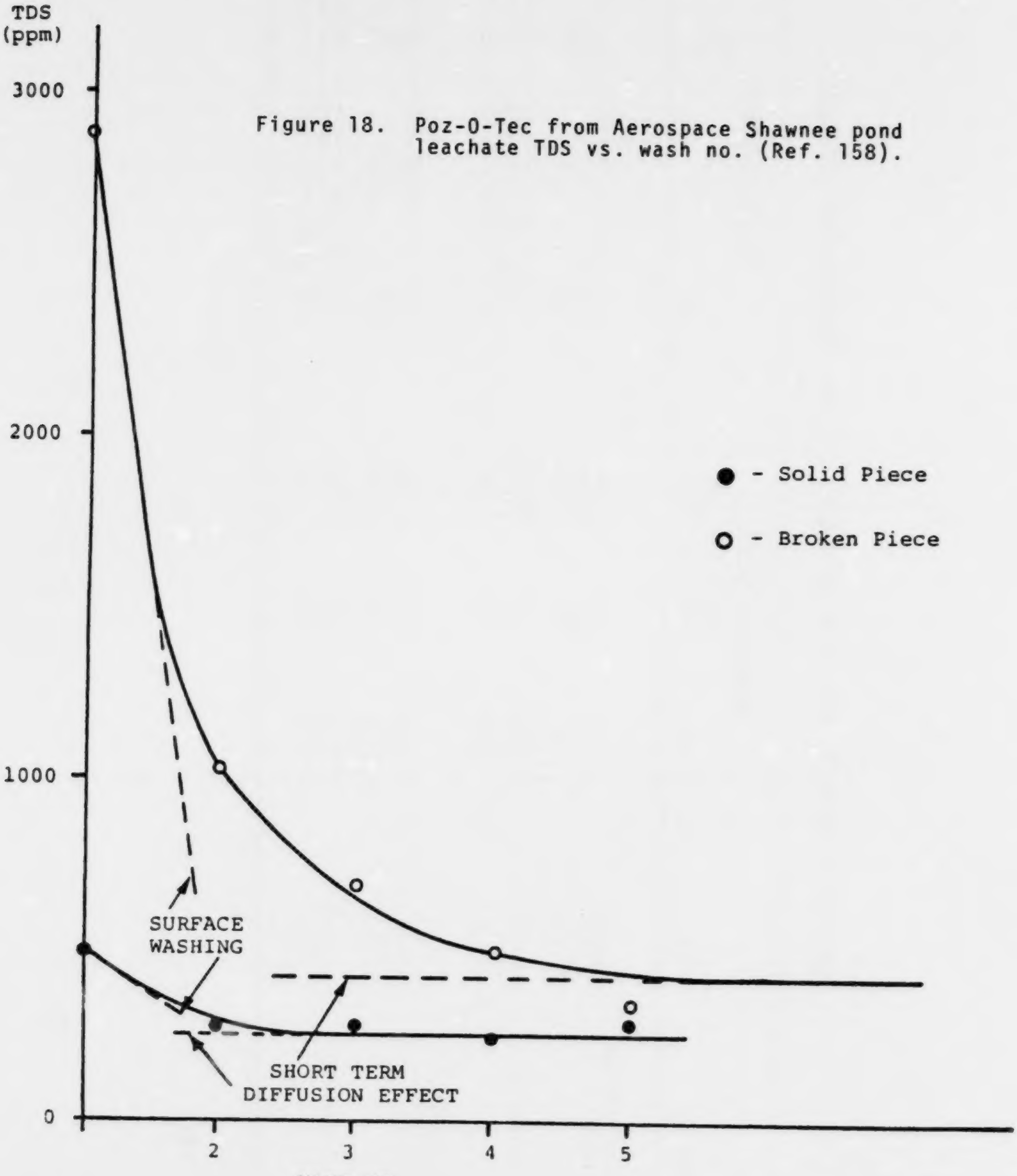

Figure 18. Poz-O-Tec from Aerospace Shawnee pond leachate TDS vs. wash no. (Ref. 158).

33 utility plants either continuously or intermittently add to or collect fly ash with scrubbed SO_2. The pozzolanic reactions of fly ash with unreacted lime or limestone in the FGD sludge produces a more stabilized waste product. This reaction was detailed in the previous discussion on stabilization.

Several power plants also dispose of bottom ash/slag with FGD sludge. Bottom ash contributes silicates and lime to the pozzolanic reaction, although these constituents are not as available as they are in fly ash, due to the larger particle size and relative insolubility of the slag matrix. Those plants that do combine slag with sludge during disposal have observed that the slag aids in preventing wind erosion and associated fugitive dust emissions. One potential stabilization process includes a material similar to boiler slag, blast furnace slag, as a major ingredient.

FGD Sludge Combined with Mine Tailings or Overburden--

The combination of FGD sludge with mine waste is feasible for the reclamation of strip mines. One codisposal alternative might consist of dumping the sludge, followed by the mine waste, directly into the pit. However, the resulting site would have questionable foundation strength unless the sludge is adequately stabilized prior to disposal. The preferable method of combination might be to mix the mine waste and the FGD sludge before replacement in the mine. This mixing procedure would also suppress the generation of acid mine drainage.

FGD Sludge Combined with Acid Mine Drainage (AMD)--

Traditionally, virgin materials such as limestone, sodium carbonate, hydrated lime, and caustic soda have been used for neutralization of acid mine drainage. Recent investigations have emphasized combining the FGD sludge with AMD for acid and soluble iron control. This procedure would depend on the unreacted alkali species in the FGD sludge for neutralization; consequently, a larger amount of FGD sludge than virgin reagents would be required. This factor renders the use of FGD sludge for control of acid mine drainage highly site specific, depending upon reagent availability. Questions have also been raised concerning possible detrimental environmental effects of sludge utilization, such as the formation of SO_2 and the presence of high levels of trace metals. No commercial operations of this sort exist today.

SLUDGE TRANSPORT

The proper choice of a transport mode is a function of sludge characteristics, transport distance, costs, capacity, and other factors. Methods of sludge transport presently being utilized or considered are:

- Sluicing by pipeline
- Sluicing by channel
- Truck
- Conveyor or bucket elevator
- Barge or rail

Pipe transportation of sludge is the most common mode among existing wet scrubber systems. The major areas of concern when designing a sludge piping system are the critical velocity, the flow properties of the sludge, the distance to be traversed, and any right-of-way impediments.

Predicting the flow properties of scrubber sludge is difficult. Aside from the readily measurable properties such as solids content, composition, and particle size, certain sludges, if not sufficiently dilute, exhibit thixotropic and rheopectic behavoir. These types of behavior will cause a change in fluid viscosity during transport and hence will affect the pumping capacity of the system.

Typical high flow velocities encountered in sludge piping can result in corrosion and erosion of pipes and appurtenances by sludge solids. Many of the existing lime/limestone systems thus incorporate rubber-lined pipes for protection. Due to limited operating experience, the exact nature and extent of corrosion and erosion from sludge piping are not well known and require further investigation. Table 28 describes existing commercial slurry pipelines.

To date, lined open channels have not been used for the transport of FGD sludges. However, if topography is favorable, open channels could have several advantages over closed pipelines: decreased abrasion, a wider choice of construction materials, reduced operating and maintenance costs, and decreased possibility of clogging due to sludge variations.

Truck transport of sludge is used when (1) the sludge is too thick to pipe, as is the case after secondary dewatering or fixation; (2) the sludge is removed to a distant disposal site, or (3) no cheaper alternative is feasible. The cost of truck transport is specific to the area in question; related variables include wage rates, distance, load limits, cycle times, and terms of existing truck. The operating variables associated with FGD sludge trucking are not fully known because of the differences in sludge character, but investigations are presently under way in this area. Technology transfer from studies of sewage sludge truck transport (e.g., Los Angeles and Orange Counties, California) appears relevant.

Several years ago, Combustion Engineering assessed the handling characteristics of untreated FGD sludge. Two truckloads (flat bottom and round bottom) were driven nonstop from the

TABLE 28.* DESCRIPTION OF SEVERAL COMMERCIAL SLURRY PIPELINES

Pipeline	Location	Material	Length (miles)	Diameter (inches)	Throughput (million tons per year)	Solids (specific gravity)	Weight (percent solids)	Years in Operation or Status†
Consolidation Coal	Ohio	Coal	108	10	1.30	1.40	52	6#
American Gilsonite	Utah	Gilsonite	72	6	0.38	1.05	46	11
Rugby Cement	England	Limestone	57	10	0.70	2.70	61	5
Colombia Cement	Colombia	Limestone	9.2	5	0.35	2.70	55	25
South African Companies	South Africa	Gold tailings	21.5	6 & 9	1.05	2.70	50	14
Savage River Mines	Tasmania	Iron concentrate	54	9	2.25	4.90	60	2
Black Mesa Pipeline, Inc.	Arizona	Coal	273	18	5.70	1.40	50	In start-up phase
Hyperion Wastewater Treatment Plant	Los Angeles	Digested sewage sludge & effluent	7.5	22	--	1.80	1.0	11
Mogden Wastewater Treatment Plant	England	Digested sewage sludge	7	12	--	1.80	4.0	33

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*Ref. 129

†As of 1971

#Commercial operation ceased in 1963 for non-technical reasons. Now maintained in standby condition.

TABLE 28* (Continued)

Pipeline	Location	Material	Length (miles)	Diameter (inches)	Throughput (million tons per year)	Solids (specific gravity)	Weight (percent solids)	Years in Operation or Status†
Easterly Pollution Control Center	Cleveland, Ohio	Raw sludge	13	12	--	1.80	2.5	32
CAPCO Bruce Mansfield	Penna., W. Va.	FGD sludge	7	12	6.5	--	7.5	1

*Ref. 129
†As of 1971

Kansas Power and Light Lawrence Station to Dulles Airport in Washington, D.C. The sludge, which had been stored in a settling pond for six months, was dredged up and drained for 24 hours prior to loading. No leakage other than water was observed during the trip. Final unloading of the flat-bottom trailer required the aid of a backhoe, while the sludge slid readily from the round-bottom trailer (Ref. 100).

Sludge treated by the Dravo fixation process has been trucked from the Duquesne Light Company's Phillips Station to a nearby landfill with no major problems. Dravo has concluded, however, that the large volume of sludge that would be generated at a typical power plant would not lend itself to economical truck transport, since as many as 40 trucks per hour would be required for complete removal. Dravo has since switched emphasis to piping of a thickened slurry -- a mode of transport also in use at the CAPCO Bruce Mansfiled plant (Ref. 157).

Sludge filter cake from the Paddy's Run No. 6 (LG&E) FGD system is trucked 1/2 mi to a borrow pit for disposal, at a cost of $.55/t (Ref. 129).

The use of conveyors and bucket elevators to transport dried or dewatered sludge should find increased application as the number of large-scale fixation and dewatering processes increases. Solids content is critical to the feasibility of belt conveyors, while bucket elevators are somewhat more versatile. Belt conveyors have been employed at several FGD operations, including Paddy's Run No. 6 and Caterpillar Tractor's Joliet pilot plant. The automated conveyor at Caterpillar (double alkali, 54-62 percent solids cake) has performed well, although periodic cleaning has been required to remove sludge from the idlers during cold weather (Ref. 52).

The feasibility of rail or barge transport of sludge is site specific. Barge transport, probably the most economical mode, is dependent on accessibility to navigable waterways. Rail transport is competitive with trucking for long distance hauls and is more widely accessible. Neither mode has been used to date for FGD sludges. Loading/unloading problems may be encountered with treated or mechanically dewatered sludges; primary dewatering produces a sludge with a viscosity comparable to that of certain commercial fuel oil grades that are readily pumpable.

FGD SLUDGE DISPOSAL TECHNOLOGY

The disposal of FGD sludges has been the subject of much research in recent years. A primary concern has been the potential for environmental degradation from the sludge and its constituents, both at the disposal site and in the surrounding ecosystem. Forty-eight FGD systems have been implemented sludge disposal systems are presently on line. Selection of these systems has been dependent primarily on cost and land availability.

The general categories of available disposal options include:

- Ponding (lined or unlined)
- Landfill
- Disposal to oceans
- Disposal to mines

The following is a discussion of these alternatives as they are practiced today.

Ponding

The use of ponds for waste disposal has been practiced by many industries, including fertilizer manufacturing, phosphate and coal mines. The design and operation of disposal ponds is well documented, as are the guidelines and standards used by these industries.

Ponding research has centered around two areas of study: (1) the actual degree of leaching encountered from lined and unlined ponds; and (2) the most effective means of containing contaminants within the disposal area.

Unlined Ponds--

The use of unlined disposal ponds is typically the least expensive method of sludge disposal. This technique, however, has been subject to criticism, primarily due to the potential for sludge contaminants to enter the groundwater. Nonetheless, 20 of the FGD sludge disposal systems in operation use unlined ponding for either intermediate clarifying or ultimate disposal. The use of unlined ponds for sludge disposal is expected to continue pending regulation of the practice.

The degree of leaching of contaminants from the pond is dependent on several factors: the hydrostatic head in the pond, which forces percolation through the pond bottom; the nature of the sludge -- primarily the permeability and the solubility of contaminants it contains; and finally, the characteristics of the soil beneath the pond, which are very important.

Lined Ponds--

The use of liners for sludge disposal ponds has recently received much attention. Liners serve both to reduce pollutant mobility and to retain water for recycle. A major deterrent thus far has been the high cost and questionable longevity of available liner materials. For the purposes of this report, "liner" refers to any material which is not native to the disposal site and is used to decrease the rate of mass transport.

The following criteria are considered important when selecting a pond liner material (Ref. 129):

- High strength and elasticity
- Good weatherability and long life expectancy
- Resistance to bacterial and fungous attack
- Ease of repair

In addition to an acceptable liner, the pond design may include a leakage detection system. One such system consists of underbed drainage channels which collect the leakage in a visible sump for periodic observation. Other methods of visible detection include standpipes and wells. Techniques of measuring ground resistivity have been developed and may also be used for this purpose.

A variety of liners for sludge ponds are commercially available. Synthetic liners use various polymeric materials, e.g., plastic or rubber; other liners include clay, stabilized sludge, admixed and asphaltic materials. Table 29 summarizes the characteristics of available pond liners (Ref. 139).

Detailed characteristics of the various pond liners have been discussed in several other studies (Ref. 129, 139). It appears that most liners, particularly those of the synthetic flexible variety, are superior to clay in permeability. Some controversy exists, however, with regard to material longevity. While some clays are thought to be longer lasting than synthetic liners, studies have shown accelerated deterioration of clay through extended ion exchange. Further investigation of liners is necessary before selection criteria can be properly formulated.

Results have been reported (Ref. 59) on the current evaluation of liner materials exposed to typical landfill leachate. After one year of exposure it was reported that:

- No significant change in water permeability was noted in any of the liners;

- The admix materials, particularly the soil asphalts, generally lost compressive strength;

- The asphalt liners absorbed some leachate but otherwise changed little during exposure;

TABLE 29.* POND LINER MATERIAL CHARACTERISTICS

Material	Thickness,[a] mil	Thickness,[a] in.	Permeability, cm/sec	Life expectancy, yr	Dirt cover[b]	Average installed[c] Cost, $/sq yd	Notes
Flexible							
Polyethylene	10	-	d	20	Yes	0.70	
Polyvinyl chloride	10-20	-	d	20	Yes	1.10-1.50	
Hypalon	30	-	d	20+	No	3.25	
Chlorinated polyethylene	30	-	d	20+	No	3.25	
Petromat fabric	-	1/16-1/8	d	20+	No	2.00	
Butyl rubber	30	-	d	20	No	2.80	
EPDM rubber	30	-	d	20	No	4.00	
Polyester fiberglass	65	-	d	20+	No	4.75	
Nonflexible							
Soil cement	-	6	About 10^{-6}	20+	No	1.00	e,f
Concrete	-	6	About 10^{-8}	50+[g]	No	3.75-4.75	e,f
Clay	-	Up to 18	10^{-5} to 10^{-8}	50+[g]	No	1.00-6.00	e,h
Asphalt concrete	-	6	d	50+[g]	No	4.00	e
Gunite	-	3	d	20+[g]	No	6.30	e,f
Pozzolan stabilized base	-	2-6	10^{-5} to 10^{-7}	50+[g]	No	3.85	

* Ref. 139

[a] Commonly used
[b] Protection from ultraviolet rays
[c] See Section 7.1
[d] Superior to clay
[e] Affected by wet/dry and hot/cold cycles
[f] Subject to sulfate attack
[g] Aerospace Corp. estimates
[h] Possible breakdown due to ion exchange

To convert from	to	Multiply by
sq yd	sq m	0.8361
mil	cm	0.00254
in.	cm	2.54

- The polymeric membranes swelled to varying degrees (by absorption of leachate)

- Swelling of polymeric membranes can increase membrane permeability to water and possibly to dissolved components;

- The polymeric membranes showed a decrease in tensile strength and hardness but generally retained puncture and tear strengths;

It should be noted that the sanitary landfill leachate used in this study is not identical to FGD leachate. However, the study may yield insight into compatibility of FGD leachate and pond liners. Polymeric, admix, and asphaltic materials were used as liners.

The U.S. Army Corps of Engineers Waterways Experiment Station (WES) is conducting a program to (1) determine the compatibility of 18 liner materials with flue gas cleaning (FGD) wastes and associated liquors and leachates; (2) estimate the length of life for the liners; and (3) assess the economics involved with purchase and placement (including disposal area construction) of various liner materials. A review of the literature was made to evaluate potential liner materials, including admixed materials (e.g., soil cements, asphalt cements, stabilized FGC waste), flexible materials (e.g., polyvinyl chloride, polyethylene), and sprayed-on materials (e.g., plastics, asphalts, sulfur).

A total of 18 liner materials was selected for use in the experiment; these are shown in Table 30. Each liner material is being exposed to two different sludges, one being a lime-scrubbed FGD waste from the Duquesne Light Company Phillips Station and the other a limestone-scrubbed waste from the Commonwealth Edison Will County Station. The liners will remain exposed to the sludge for two years under a simulated sludge depth of 30 feet. Physical property tests were performed on each liner material upon receipt and after one year (March 1977). Results of the one-year test are not yet available. A final report is expected to be issued in the spring of 1978. (Ref. 96).

Landfill

FGC sludges are used as landfill in several locations. For the purposes of this study, a sludge is classified as landfill material only if (1) it is stabilized to a solid without a head of water, or if (2) the sludge is dewatered mechanically or thermally to a solid material. Both dewatering and stabilization were discussed in a previous section of this report.

TABLE 30.* LINER MATERIALS

Material	Material Type	Manufacturer
Sprayon Type		
DCA-1295	Polyvinyl acetate	Union Carbide
Dynatech Formulation 267	Natural rubber latex	Dynatech Research and Development Co.
Uniroyal	Natural latex	Uniroyal, Inc.
Aerospray 70	Polyvinyl acetate	American Cyanamid
AC 40	Asphalt cement	Globe Asphalt
SSK	Slow setting cationic emulsified asphalt	Globe Asphalt
Admixes		
Cement	-	Dundee Cement Co.
Lime	-	Williams Keith Lime Co.
Fly Ash	-	Amax Fly Ash Co.
Cement with Lime	-	-
Cement with Fly Ash	-	-
Lime with Fly Ash	-	-
M179	Polymer bentonite blend	Dowell Div. of Dow Chemical
Guartec (UF)	A light grey powder	General Mills
Analine, Furfural	-	GAF Corp (Analine) and General Mills (furfural)
Asphalt Concrete Paving	-	Local Contractors
Prefabricated Membranes		
Liner	Elasticized polyolefin (30 mil)	The Goodyear Tire and Rubber Co.
T-16	Black neoprene-coated nylon-reinforced fabric	Reeves Brothers, Inc.

*Ref. 96

Dewatering for landfill disposal is currently practiced at six utility FGD systems. For example, at the Louisville Gas and Electric Paddy's Run Station, clarifier underflow is vacuum filtered to between 40 and 60 percent solids and trucked to a nearby borrow pit for disposal. At the pit, the sludge is mixed with fly ash and compacted with a bulldozer. Although the sludge solids contain as much as 98 percent calcium sulfite, rewatering of the sludge has not been a problem (Ref. 142).

Industrial FGC system users have favored landfilling of dewatered sludge. In the U.S., six of the eight industrial plants are currently utilizing this disposal scheme. In Japan, mechanical dewatering is necessary if gypsum is to be generated and sold from the FGC installations. Current marketing difficulties have forced Japanese utilities to establish temporary landfill operations.

Structural stability is an important consideration in proper landfill operation and site reclamation. While some FGD sludges can provide sufficient load-bearing strength to support equipment and light construction, others may require some type of stabilization to meet these requirements. Chemical treatment of FGD sludge is presently practiced at several power plants, including Duquesne Light Co., Phillips and Elrama Stations (Pittsburgh, Pennsylvania), and Commonwealth Edison, Will County Station (Chicago, Illinois). The need for stabilization has generally been dictated by the value of local land and by state and local laws regarding land reclamation.

The leaching of salts and trace metals from a sludge landfill can be minimized through proper design and operation. Although the lack of a hydraulic driving force is a primary advantage of landfill over ponding, rewatering of the sludge can yield a mass with the same potential for groundwater contamination as raw sludge. Consequently, landfilled dewatered sludge must be protected from liquid infiltration. For the disposal of hazardous wastes, infiltration of the site is controlled either by covering the material periodically with a low-permeability soil (sanitary landfill) or encapsulating the disposal site after decommissioning with a low-permeability material such as a plastic liner, asphalt, or high clay-content soil.

Ocean Disposal

Ocean disposal of FGD sludges is an option that is perhaps available to throw away system users with economic access to the ocean. New ocean disposal initiatives are discouraged by regulatory agencies. Arthur D. Little, Inc. (ADL), in a study sponsored by EPA, is currently investigating the feasibility of ocean disposal of FGD sludges.

There are two alternative ocean areas for sludge disposal:

- Shallow ocean (on the continental shelf)
- Deep ocean (off shelf)

Each area has a distinctly different ecosystem and is therefore subject to a different set of criteria for evaluating environmental impact.

The continental shelf is mainly a euphotic zone and is rich in ecological diversity. It is, therefore, the major ocean site for biomass production that is important to man. A system of such magnitude is quite fragile and highly susceptible to interference from foreign sources. In contrast, the deep ocean is a relatively barren area of low productivity and high resistivity to change. This would be the ideal area for sludge disposal.

Transportation of sludge for ocean disposal can be accomplished either by ship, barge, or pipeline. The mode of transportation with the lowest projected costs (not considering regulatory constraints) is the conventional bottom dump barge.

The A.D. Little study identified the following as potential environmental concerns when disposing of FGD sludge to oceans (Ref. 78):

"1. Ocean-floor sedimentation - The particle (crystal) sizes of most untreated FGC wastes are much smaller than the coarse-grained sand particles of the ocean floor, which are most conducive to the marine life found on the continental shelf. Therefore, deposition of these wastes in large quantities may have an undesirable effect in the relatively shallow continental shelf area, particularly if disposal results in "paving" of the ocean floor.

2. Solids suspended in the water column - Settling of disposed FGC wastes toward the ocean floor through the water column, as well as resuspension of solids from the ocean floor, would expose various types of marine life to elevated concentrations of suspended sediments. The effects of sediments vary from minimal to serious, depending on the organism involved.

3. Sulfite-rich wastes - Many FGC wastes contain significant quantities of calcium sulfite hemihydrate, presenting a potential problem of sulfite toxicity to marine life and a potential chemical oxygen demand (COD) problem if oxidation to sulfate occurs. The actual impacts of sulfite toxicity, dissolution and oxidation will require further investigation.

4. Trace contamination in wastes-Untreated and treated FGC wastes may contain several trace elements in concentrations in excess of acceptable levels for the marine environment. Significant dilution of the wastes with seawater (i.e., dispersion) may be necessary for ocean disposal to be acceptable."

The alternative ocean disposal schemes being evaluated by A. D. Little include:

- Dispersed dumping on the continental shelf
- Dispersed dumping off the continental shelf
- Concentrated dumping of treated sludge
- Conventional dumping off the continental shelf

The State University of New York (SUNY), Stony Brook campus is studying use of stabilized FGD sludge blocks (IUCS Poz-O-Tec) to create artificial reefs for marine habitats. The research funded by the New York State ERDA and Public Service Commission, is being performed in two stages. The first stage consists of a laboratory investigation into the chemical and physical reactions of the sludge with seawater and marine flora and fauna. The second stage is a field evaluation of a sludge artificial reef in a bay near the SUNY campus.

The laboratory tests are nearing completion. Published results are expected by October 1977. After one month of kinetic studies, rapid initial solubilization of calcium and certain other species has been noted. The rates of solubilization slowed as equilibrium conditions were reached. No appreciable trace metal leaching was noted. The explanation put forth for this phenomenon is that the oxidized surface of the sludge prevents migration of seawater into the blocks. It was also noted that the sludge compressive strength increased as the duration of exposure to the seawater increased.

The second stage was initiated in May 1977 and is expected to continue for two to five years. One cu ft FGD sludge blocks and a control cement block were placed ten feet under water in a marine bay near the SUNY campus. Physical and chemical reactions within the blocks will be studied. After two weeks of submersion, rapid attachment of benthic macroorganisms to the blocks was noted irrespective of their composition.

Mine Disposal

The feasibility of FGD sludge disposal to mines is of interest particularly to the many mine-mouth, coal-fired power plants. Sludge disposal to mines has the advantages of (1) minimal transportation requirements, when a mine is nearby; (2) minimal incremental land use; (3) possible mine reclamation; and (4) serving as a pH amendment for mine tailings. The principal concerns are possible interruption of mining operations, contamination of ground or surface waters, and fugitive emissions and runoff. Several studies are currently under way to evaluate the feasibility of various mine disposal alternatives.

Arthur D. Little, Inc. is also evaluating the feasibility of mine disposal of FGD sludges. A review of six selected mine categories has suggested that the most promising sites are surface area strip mines, underground room and pillar limestone mines, and load-zinc mines. Table 31 lists the evaluation of various mine types and the feasibility of sludge disposal in the mines (Ref. 4).

The most promising surface mine disposal sites appear to be located in the midwestern United States. These mines have substantial capacity for receiving FGD wastes, and disposal within existing mining operations appears to be technically feasible. The disadvantage to surface mine disposal in the west is the limited amount of rainfall available to dilute FGD sludge leachate. In any instance, FGD sludge disposal within surface mines will assist in returning the land to its original elevation after covering with overburden (Ref. 78).

Eastern and midwestern room and pillar coal mines were also determined to be promising disposal sites. Although injection of FGD sludge into deep mines could complicate onging mining operations, it has two distinct advantages: (1) the long-term control of mine subsidence if dewatered and/or stabilized, and (2) the prevention of acid mine drainage and neutralization of acid which is generated (Ref. 78).

Both surface mine and underground mine disposal of FGD sludge can prevent the potential for groundwater contamination by sludge leachate. This is particularly true for untreated sludge. Stabilization, although desirable for subsidence control, leaching control, and backfill material, is more expensive than simple untreated sludge disposal. The feasibility of FGD sludge disposal to mines is strongly dependent on the hydrogeology of the surrounding area.

Radian Corporation has been studying the physics of mine subsidence and its impact on the use of FGD sludge as backfill. It has been determined that there is a trade-off between viscosity of the sludge and allowable settlement in the mine using untreated FGD sludge. The optimal range for both parameters is a function of the sludge and its behavior at various solids contents. The study has concluded that sludge combined with coal waste can provide the best means of preventing mine subsidence while disposing of waste. The detailed study results should be available in late 1977 (Ref. 78).

TABLE 31.* GENERAL MINE CHARACTERISTICS

Mine Type (Region)	Rainfall/Evap. "/yr.	Mine Water Quality	Sludge Type	Sludge Disposal
Area strip coal mine (Interior province)	40/36	Neutral/basic	Dry+	Easy
Area strip coal mine (Western province)	15/42	Neutral	Dry	Easy
Room & pillar coal mines				
(Eastern)	1) 40/32	None	Dry or	Difficult
(Eastern)	2) 40/32	Acid (pH 3-5)	Slurry	Difficult
(Interior & mountain)	3) 40&15/36&42	Neutral	Slurry	Difficult
Longwall coal mines (Eastern & mountain)	40/32 15/42	None Acid (pH 3-5)	Dry	Difficult
Room & pillar load zinc mines (Interior)	40/36	Alkaline (pH-8)	Dry or Slurry	Difficult
Room & pillar limestone mines (Interior - actually in 12 states)	40/36	None	Dry or Slurry	Easy
	40/36	Alkaline	Slurry	Easy
Room & pillar salt mines (Eastern & interior)	40/32-36	None	Dry	Difficult
Old iron ore pits (Interior)	30/24	Neutral/Alk. (pH 7-8)	Dry or Slurry	Easy

*Ref. 103

+ Dry means any sludge that can be handled as a dry solid. The sludge can contain moisture and is best if it is moist (<40 percent moisture according to sludge morphology).

The Pennsylvania Department of Environmental Resources has recently received a grant from EPA to assess the feasibility of using FGC wastes to prevent mine subsidence and reduce acid drainage. Results of that study are not expected before 1978.

FGD SLUDGE UTILIZATION

Sludge utilization is a desirable alternative to sludge disposal. It relieves the FGD user of the burden of sludge accumulation and disposal. In addition, utilization can provide the user with a marketable commodity from an otherwise expendable by-product. A discussion of current and proposed sludge utilization practices was presented in Section V.

SECTION VIII

ENVIRONMENTAL CONSIDERATIONS

DISPOSAL SITE CHARACTERISTICS

The disposal site characteristics which influence the environmental impact of FGC waste disposal include:

- Present and projected land use
- Topography
- Hydrology and geology
- Meterology

These site characteristics when combined with the sludge characteristics, economics, and other disposal variables, will determine the optimal solution to the disposal problem. The variety of these relationships indicates that no general solution is appropriate to all areas. Some disposal sites may have little significant environmental impact regardless of sludge characteristics and disposal management variables. Other sites may be very sensitive to the type of disposal operation employed or to sludge characteristics.

The environmental impacts associated with each of the site characteristics will be examined in the following subsections. In addition, a discussion of the mass transport phenomenon associated with contaminants transmitted from the disposal site to the general environment through the groundwater will be included in the section on hydrology and geology.

Present and Projected Land Use

The present and potential future land use of a proposed disposal site will influence the disposal technique to be utilized. A primary distinction can be made between urban and rural land uses. Typically in urban locations, property values are higher than in rural areas. Therefore, techniques which utilize less land and/or generate a fill material of adequate bearing strength would be cost-effective in urban areas.

Potential land use will be at least partially determined by present methods of FGD sludge disposal. For example, depending upon sludge characteristics, the use of pond disposal of unstabilized sludge may result in a site with virtually no bearing strength. In urban locations, this lack of mechanical stability would prevent future use of the site for anything more than the lightest duty applications (e.g., if suitable cover material were provided, such a site could support a park). On the other hand, the disposal of stabilized materials might maintain the potential for future site use.

The optimum disposal scheme will be strongly influenced by economic factors. Trade-offs between the cost of stabilizing the fill area would be considered as opposed to the use of an unstabilized pond which would drastically reduce property values.

It should be noted that the property tax structure of most metropolitan areas will introduce distortions into any economic calculations. Property taxes are often based upon the value of the land for its highest potential use. If the disposal site is used for unstabilized sludge, the site would have an essentially zero value for any other purpose; after decommissioning, it would be taxed at a very low rate. If the site receives structurally stable or fixated sludges, it will have a higher potential value and be subject to correspondingly high property taxes.

Rural locations are generally characterized by relatively low land values. At most rural sites, land value is, to a large degree, a reflection of its productivity. For example, prime agricultural land may sell for somewhere in the range of $500 to $2,000 per acre; grazing land may range from a few dollars to $100 an acre.

At most rural sites, the land cost of disposed sludge is down in the few cents per ton category. These low relative costs make property tax and direct land purchase costs insignificant terms when determining the optimum disposal technique for a particular site.

Topography

Topography of the disposal site and adjacent areas influences the potential environmental impact of the disposal operations in four ways, as follows:

- Drainage structures should be designed to prevent the intrusion of rainwater runoff into the disposal area;
- FGD sludge retention structures (dikes, dams, etc.) should be designed more securely when topography would allow sludge release by retention structure failure to flow to nearby surface waters;

- As discussed in a later subsection, the relative elevations of the disposal pond surface, pond bottom and groundwater have a strong influence upon the mass transport of FGD contaminants to the groundwater; and

- Proper use of topography can minimize the unaesthetic visual impacts of the disposal site operation.

Retention structure failure and subsequent release of large volumes of sludge to surface waters (rivers, lakes, etc.) would have catastrophic effect upon the surface water biota. When possible, disposal sites should be located so that accidental sludge release would not flow to nearby surface waters. If such a desirable location is not available, the retention structures should be designed to high safety standards, including back-up structures (e.g. a double dike system).

Hydrology and Geology

Generally, the impact of the FGD disposal site upon the groundwater resources below the site is of major concern to regulatory agencies. Of interest is the mass transport of contaminants form the FGD sludge to the groundwater in a pathway which includes:

1. Quality and quantity of leachate generated by the in-place sludge;

2. The rate at which leachate permeates through the retention structure (usually a pond liner), if a liner is installed;

3. The rate at which individual contaminants in the leachate which escapes the retention structure travel through the underlying soil; and

4. The effect of the contaminants which reach the groundwater aquifer upon the quality of the groundwater.

This subsection discusses the hydrological and geological factors involved in 3 and 4, above.

Groundwater quality can range from highly desirable drinking water to water that is nonpotable. These variations in existing groundwater quality can be of natural or artificial orifin. In many areas of the southwest, it is common to find shallow, highly saline water due to concentration by evaporation or a preponderance of exchangeable cations. The water quality in many of these areas may be worse than the quality of the leachate generated in a disposal site. Where poor groundwater underlies a disposal site, the question of groundwater pollution from contaminant mass transport is perhaps academic.

Where potentially useful water underlies a disposal area, it is necessary to consider the mass transport of contaminants from the site to the water table in order to evaluate the potential environmental significance of any given disposal practice. The term "mass transport" as it is used here, refers to the movement of contaminants from a disposal site to the surrounding environment. The rate of mass transport is perhaps the most important factor in estimating groundwater pollution potential. This rate is a function of many variables, including:

- The concentration of contaminants in the leachate (c)
- The permeability of the sludge or the underlying soil (whichever is lower), (k)
- The hydraulic gradient, (∇H)
- The ion exchange capacity of the underlying material
- Other possible attentuation mechanisms in the soil (adsorption, etc.)

The equations which determine flow rates through soils are mathematically similar to equations found in other areas of science. They incorporate most of the above-named variables (attenuation and ion exchange being incorporated into the "retardation factor," R). The specifics of mass transport theory are discussed briefly in Appendix B and in the literature (Ref. 134, 172).

The effect of various disposal techniques and the associated site variables on the overall mass transport of contaminants are summarized in Table 32. This summary table provides information on the relative effects of various disposal techniques and site variables on the overall mass transport of the contaminants from the site.

As can be seen from Table 32, different disposal techniques or site variables affect the mass transport by changing parameters. For example, clay liners in the bottom of ponds will reduce the flow rate through the bottom of the pond by decreasing the permeability; while locating a pond in a high water table, low horizontal hydraulic gradient area will decrease the mass transport by decreasing the hydraulic gradient. This will also decrease the flow rate. Locating the disposal site above clay and/or organic soils which have high cation exchange capacity will increase the retention factor. This will decrease the mass transport of some contaminants by slowing cation movement.

While research has been concerned with mass transport, long term predictability of mass transport from a disposal site

TABLE 32. RELATIVE EFFECTS OF VARIABLES ON MASS TRANSPORT OF CONTAMINANTS FROM DISPOSAL SITE TO GROUNDWATER

	Mass Transport = $(C, k_{soil}, k_{fill}, \nabla \cdot H, R_{soil})$							
Variable	C (mg/l)	k_{soil} (cm/sec)	k_{fill} (cm/sec)	$\nabla \cdot H(\frac{dynes}{cm^3})$	R	Long Term Predictability	Reduction Factor	Overall Effect on Mass Transfer/Comment
Disposal Technique								
. unlined pond	--	10^{-4}	10^{-4}	10	1 for anions 10^{-2} for cations	--	-1-	. Base line case*
. clay lined pond	--	10^{-7}-10^{-8}	--	--	--	Fair	10^3-10^4	. Depends upon k_{soil} decrease
. membrane lined pond	--	--	--	0.0	--	Poor	∞	. Depends upon long-term integrity of liner
. stabilization								
. high k product	Decrease	--	--	--	--	Fair	1-10^3	. Depends upon decreased solubility within fill
. low k product	May decrease	--	10^{-5}-10^{-7}	--	--	Fair	10-10^6	. Effects of k_{fill} decrease only significant if $k_{fill} << k_{soil}$
Site Variables								
. low k_{soil}	--	10^{-7}-10^{-8}	--	--	May decrease for cations	Good	10^3-10^4	. Limits flow rate by low k_{soil}- only significant when $k_{soil} << k_{fill}$
. soil w/high ion exchange	--	--	--	--	1 - anions 10^{-3}-10^{-4} cations	Fair	Breakthru phenomenon	. Depends upon cation exchange capacity
. hydrology								
. high watertable low horizontal gradient	--	--	--	10^{-2}-10^{-3}	--	Excellent	10^3-10^4	. Minimizes hydraulic gradient
. low watertable	--	--	--	10-20	--	Excellent	.5-1	. Provides maximum flow rate but provides time delay (on the order of one year)
. meteorology								
. high evap. rate vs. precipitation rate	May increase	--	--	Decreases for semi-dry fill	--	Good	1-∞	. Decreases transport of solubility limited compounds by reducing liquid flow rate (only significant when evap. rate >perculation rate $(k_{soil} * \nabla \cdot H)$)

-- = no change from base line case

* unlined pond above relatively permeable soil with deep water table.

where:
C = liquid phase concentration of leachate
k = permeability coefficient
$\nabla \cdot H$ = gradient of the hydraulic potential
R = retardation factor related to adsorption of impurities on surfaces

is limited to purely physical parameters. Those effects which are dependent upon subtle chemical interactions and may change rapidly with time are far less predictable. The following is a discussion of several important physical parameters and their relation to sludge disposal.

Diffusion--

The intrinsic diffusion rate of various soluble species in water is fairly well known. Even in cases where experimental measurements of diffusion coefficients in water are unavailable, theoretical methods for calculating such diffusion coefficients are reasonably well developed. Present theoretical descriptions, based upon molecular parameters, will usually provide a diffusion coefficient within a factor of 2 of the measured value. It should be noted that the value range for diffusion coefficients of soluble species in water is on the order of 10^{-5} to $10^{-4.4}$ cm^2/sec depending upon the specific impurity in question. A more complete discussion of diffusion coefficients in liquid and of calculation techniques can be obtained from "Diffusion" by W. Jost. (Ref. 81).

Mass transport of ions through water tables and strate underlying a disposal site involves distances of many meters, usually in the 100 meter range. An idea of the extent of ion mass transport over these distances can be obtained by considering a problem in one dimension. Such a problem can be represented by a mixed pond in which a constant concentration of a particular ion sitting on top of the stationary layer of soil is in turn resting on top of a very porous layer of very fast moving underground water. Assuming further that the flow rates through this layer are zero in order to isolate the effects of the diffusion term, the problem appears as a classic barrier permeation experiment.

In this experiment, a known concentration of the species of interest is placed on one side of a barrier. The time rate of change of concentration on the other side of the barrier is zero. It begins to increase at some later time as the contaminants diffuse through the stagnant layer. There is a characteristic mathematically defined time for measuring the contaminant flow through the membrane and its appearance on the other side. This characteristic time is related to the diffusion coefficient as follows:

$$X^2 = 6\,D\,t'$$

where:

X = membrane thickness
D = dispersion coefficient
t' = time for contaminant to flow across membrane

Using values of 10 meters for the thickness of the soil layer under the pond and a value for the dispersion coefficient of 10^{-6} cm^2/sec (including the corrections for the void fraction and path length changes in translating liquid measurements into our multi-based system of soils and water), a value on the order of 5,300 years is obtained for this characteristic time. In other words, if a salt solution is placed on one side of a 10 meter thick layer of non-absorbing soil (such as fine sand) with fresh water on the other, it would take approximately 5,000 years before the salts diffuse to the other side.

The preceding discussion indicates that the dispersion terms in the overall mass transport equation are insignificant for realistic distances under conditions of no velocity or hydraulic head. From an environmental standpoint, even after the 5,000-year period, the rate of diffusive mass transport will be insignificant. This is due to the large distances involved and reflects the fact that these distances enter the solutions of mass transport equations as the distance squared. If distances on the order of 100 meters - the more probable distances to any drinking water well - are considered, the time delay would be increased by a factor of 100. This results in a characteristic time on the order of five hundred thousand years.

Convection--

There can be no significant mass transport from the site independent of the variables associated with sludge composition or disposal technique without convection terms. The convective flow term in the mass transport equation (Appendix B) involves the retardation factor, the velocity of the flowing fluid, and the concentration of the particular ion in question. Velocity is determined by both the permeability and hydraulic conductivity of the material at the point in question, and the gradient of the hydraulic permeability potential.

The permeabilities of flue gas cleaning sludge are relatively uniform throughout the sludge mass. The permeabilities in the surrounding area, however, may vary considerably. When combined with the associated hydraulic gradients, these same permeabilities in the soil provide analysis of the groundwater flow including both natural groundwater and the leachate from the disposal site.

In general, stabilization processes decrease the permeability of FGD sludges (see Section VII). Stabilization in this sense is crucial when the sludge permeability becomes less than that of the underlying soil (i.e., becomes the rate controlling step). If the soils underlying the site are less permeable than the stabilized material or even with the same order of magnitude, the stabilization of the material will change the overall flow rate from the site only if the material is saturated. Proper site management is therefore essential in preventing saturation. The only advantage of the fixation process would then be the resulting decrease in concentration of many ions, which is often related to pH changes occurring during stabilization.

Since permeability is highly variable and depends upon a detailed understanding of the underground strata, a detailed solution to the mass transport equation is not usually possible for three-dimensional flow. Nonetheless, the effect of changes in various parameters entering the mass transport equation can be estimated without a detailed calculation.

The use of clay lined FGD sludge ponds will affect the overall rate of mass transport by creating an artificial low permeability layer beneath the site. This low permeability layer will decrease the overall mass transport from the site. The use of clay as a liner material will also tend to cause a temporary decrease in the retention factor R. The use of impermeable liner materials such as hypalon, polyvinylchloride, and similar impermeable membranes arrest mass transport of contaminants from the site by stopping downward movement of the leachate. Most of the materials being used for liners are specified for temporary duty and have a useful life limited to at most a few decades.

Hydraulic Potential--This is the basic driving force for convective liquid phase mass transport. In simple terms, the mass transport rate for leachate leaving the pond area depends upon the difference in elevation between the free liquid level in the pond and the surrounding water table. For two otherwise identical disposal situations (characterized by the same soil properties, permeabilities, sludge characteristics, and pond design), significantly different mass transport rates can be calculated for two different depths of water tables. In areas with deep water tables, where density differences are favorable, the leachate can migrate straight down to the water table and then spread out, possibly mixing with the groundwater. In very high water table areas, the driving force for vertical movement is limited to diffusive mass transport. The hydraulic potential will be small. Most sites with suitable high water tables are located in low-lying areas which may be subject to flooding. It would be necessary to surround the pond with dikes in order to prevent surface water flow over the site in the event of flooding. Since all material would actually be disposed of below the water table in the pond, no hydraulic forces would be exerted on the dikes themselves under normal non-flooded conditions. If it is assumed that the water level in the pond is maintained exactly equal to the height of the water table in the surrounding areas, the only driving force for leachate movement will result from the possible small density differences between the leachate and the surrounding water. These driving forces would be very small; with any regularly encountered permeability of the soils, the overall mass transport rate for contaminants leaving the site would be negligible.

The idea of protecting the groundwater supply by disposing of the materials below the water table and actually in the groundwater itself may seem to go against intuition. A thorough evaluation of the appropriate mass transport equations makes it clear that such an engineering solution is not only feasible but optimal in terms of preventing groundwater contamination. The key to practical application of this technique is control of convection from the site to the groundwater, caused by vertical or horizontal hydraulic gradients. Horizontal hydraulic gradients can be controlled by engineering design. One such design would involve cutting a trench extending well down into the water table around the outside of the pond area. Such a trench, completely surrounding the pond, would effectively eliminate any horizontal hydraulic gradients. For the vertical gradients, the pond level need only be kept below that of the surrounding groundwater to inhibit leachate migration. The major drawback to this approach is the high cost of excavating below the water table.

The above discussion of sludge disposal below groundwater is intended to serve only as a limiting case. It does show the dependence of mass transport on convection, and how limiting convection can significantly reduce mass transport.

Limiting convection is also important to landfill operation. Although stabilized or dewatered and compacted FGD sludge has a low permeability (10^{-5} - 10^{-6} cm/sec), the resulting landfill may eventually become saturated due to capillary action, rainwater percolation, or simple groundwater flow. The control of runoff there becomes important to reducing the vertical gradient. Without convection, diffusion of contaminants in and out of a sludge landfill will contribute negligible amounts to the groundwater as demonstrated in a variety of leaching tests being used (see Section VII under "Stabilization").

Estimating Mass Transport Rates--

While the mass transport equations discussed here and in Appendix B can be solved, their solution is far too complex for day-to-day use in site selection and monitoring. "Rules of thumb" are therefore important to properly assessing potential environmental impact from sludge contaminant migration. These estimates can be used to determine the acceptability of the site, and monitoring results can be checked against these projections as a safeguard.

The site parameters which affect the mass transport are permeability, hydraulic head, and distance to the groundwater table. These parameters are all related to convection, as diffusion is assumed negligible in comparison. The rate of contaminant migration, a function of these parameters, is expressed as follows:

$$V_s = K \frac{\Delta H}{\Delta X}$$

where:

V_s = superficial velocity, cm/sec

K = coefficient of permeability, cm/sec

ΔH = hydraulic head, cm

ΔX = distance from pond to groundwater, cm

The macroscopic rate of migration, or pore velocity (V_p), would be determined from the following expression:

$$V_p = V_s/\varepsilon$$

where ε is the void fraction of the underlying soil. Based upon the calculated pore velocity, the time to reach the groundwater could then be determined from the thickness of the soil layer. The time required for contamination to show up in the monitoring wells would then be determined from the rate and distance of groundwater flow.

As an example, consider a disposal site with the following characteristics:

- Location:

  Arizona, less than 500 people within 50 Km radius - no cities greater than 10,000 population within 75 Km

- Meteorology:

  Net evaporation area, periods of high winds

- Hydrology and Geology:

  - 10 meters of clay (permeability coefficient of 10^{-8} cm/sec) overlaying 20 meters of sand aquifer with a water quality of 6,000 ppm TDS. Below this aquifer is another 10 meter clay layer (.30 void fraction) with a deep fresh water aquifer under this second clay layer.

- Distance to nearest navigable waters from disposal site 5 Km with an elevation drop of 20 meters

- 20 meter total hydraulic head to bottom of clay layer (i.e. 10 m deep pond)

- Computing:

superficial velocity = $V_S = K\frac{H}{X} = 2 \times 10^{-8}$ cm/sec

where K = permeability cm/sec

H = hydraulic head

X = thickness of clay layer

The pore velocity $V_p = V_S$/void fraction

$= 2 \times 10^{-8}/.30 = 6.6 \times 10^{-8}$ cm/sec

$= 2.1$ cm/yr

This flow rate would then be applied to the total acreage involved and the contaminant concentration in the leachate to compute mass flow. This mass flow rate would be added to the groundwater flow to determine the change in water quality (if any).

As a second example, consider a site with the following characteristics:

Location: Northeast coastal site

Meteorology: 3 meters of precipitation/year

Hydrology and Geology:

Abandoned sand and gravel quarry - 30 m deep and 20 Ha in area

Permeability - 10^{-2} cm/sec

Aquifer is 2 meters thick above clay layer

Velocity in aquifer is 1,000 m/yr

Velocity in aquifer is 1,000 m/yr

Void fraction is 0.25

Water quality is 100 TDS

Also assume the sludge is stabilized and possess a permeability coefficient of 10^{-6} cm/sec. The material is 25 meters deep.

If the drainage was poor, a unit hydraulic head would exist on the material (hard to avoid with this rainfall) and a flow rate into the aquifer on the order of 10^{-6} cm/sec over a 20 Ha area, or a total flow of 2 ℓ/sec. This flow from the fixated material could contain 2,000 ppm TDS, which could contaminate 378 ℓ/s or $12 \times 10^6 m^3$/yr of the fresh water flowing under the site beyond the 10 percent level considered previously. With a flow velocity of 1,000 m/yr, a total of approximately 9×10^5 m^3/yr of fresh water would be flowing under the site. If our 2 ℓ/s of leachate mixed with this water, we would have a concentration in the mixed plume of 227 ppm TDS, which is well over a 100 percent increase in TDS. Considering the soft nature of some waters and the high calcium hardness of FGC sludge leachate, the increase in water hardness would be even greater.

Meteorology

Local meteorology can interact with the disposal technique being employed through two primary mechanisms. The first of these relates to the characteristic evaporation/precipitation ratio at the site, and the second to the effects of wind erosion on the surface of the site if the site is dried.

Evaporation/Precipitation--

In areas with high evaporation rates relative to precipitation rates (again, as in most of the southwest United States), significant amounts of water can be evaporated from an evaporation pond. The net evaporation over precipitation rate can vary from a matter of a fraction of a meter per year to up to 2.5 meters annually. Standard meteorological evaporation pan data may show evaporation rates up as high as 3 meters a year, but when translated to actual field conditions, significantly less total evaporation will occur. A high evaporation rate allows certain types of solutions to disposal problems that are not feasible in low evaporation rate areas. Under such climatic conditions, contaminated leachate can be disposed of through evaporation.

Whether the evaporation rate of an area can be effectively utilized depends upon the detailed design of the disposal system. If the disposal area contains a totally impermeable liner, the site can eventually evaporate to dryness. All leachate will be dried by evaporation, leaving a salt residue in the bottom of the pond. However, evaporation also concentrates the leachate before drying it, thereby actually increasing the mass transport rate for the same site permeability.

Potential salt leakage from the disposal pond can be estimated from the following equation:

$$1 + \frac{\text{evaporation rate}}{\text{Leak rate}} \geq Rc$$

$$R_c = \text{concentration ratio, } \frac{\text{species solubility product}}{\text{species solution concentration}}$$

By definition R_c will always be ≥ 1. If the equation is not satisfied, soluble salts will escape the pond.

For example, many of the soluble salts (such as sodium chloride) are several orders of magnitude below their solubility limits. This would yield a R_c of approximately 10^2. Therefore, for a pond which has a net evaporation rate of two meters per year, a leak rate of less than two centimeters per year would retain the sodium chloride. If the leak rate exceeds 2 cm/yr for a single pond installation, the salts would leave the confined area of the pond and enter the underlying soils. Whether these salts would then migrate down into the water table will depend on hydraulic considerations. However, the main point is that the salts have now left the site and can no longer be controlled.

If the object of the disposal technique is to minimize the amount of salt leaving the site, it is possible to retain a significant portion of the salt even though the leak rate may be higher than the specified 2 cm/yr. This can be achieved by using a series of ponds rather than a single pond for solar evaporation. The benefits of series operation can be seen if a hypothetical series of seven ponds is considered. An input concentration for the first pond of 1/100th of the saturated concentration for the salt in question will be assumed. If each pond evaporates to the point where the concentration is double its inlet concentration before passing it along to the next pond, the leakage out of the first pond will be a relatively dilute solution of 1/50th the saturated concentration. The leakage out of the second pond will be 1/25th of the saturated concentration, and so on. The area required for the second pond is only half of the area of the first pond. By the time the water reaches the last pond, it will exceed the solubility product and the salts will begin to precipitate out. The leakage from the end pond is saturated with respect to the soluble salts, although the total area required for this last evaporation pond may be only 0.8 percent of the area required for the single pond system.

For a very dry area, where the evaporation rate is not a function of the salt in the water and with a 2 cm/yr leak rate, this hypothetical series-pond would retain about 93 percent of the salts. Under the same conditions, however, none of the salts would remain in a single pond with the same leak rate. Under actual conditions, the problem involves multiple salts with different solubility limits. This hypothetical example illustrates in broad outline the anticipated impact of series versus parallel operation for solar evaporation disposal ponds.

In areas with very high precipitation rates, significant volumes of water may enter the site every year from normal rainfall. This water can leave the site through either surface water or groundwater flows. After decommissioning the plant, it is clear that water would not be returning to it. If this water leaves the site via the groundwater system, it must have passed through the disposal materials and would, therefore, contribute to the total leachate flow leaving the site. In this case, added precipitation could stand on the site and increase the hydraulic head, thereby increasing the total leachate mass transport from the site. If the rainwater is allowed to leave through surface runoff, it may carry materials from the site. This can be partially controlled by engineering designs which allow sufficient amounts of settling. Allowing surface runoff would cause less total contamination than permitting leachate to enter the groundwater. The surface water which enters the site from precipitation only comes in limited contact with the fill material. It would not necessarily flow through the material. Therefore, the concentration of contaminants found in surface runoff is usually much less than the concentration in the leachate.

In areas without the very low relative humidities characteristic of the southwest desert areas, the operation of solar evaporation ponds in series rather than parallel produces the additional advantage of a higher net evaporation rate. This is due to the fact that the initial series evaporation ponds contain relatively dilute solutions and have correspondingly higher evaporation rates than a single pond containing a very concentrated solution.

In summary, areas of net evaporation and net precipitation pose different problems to engineers designing FGD sludge disposal systems. Net evaporation areas tend to concentrate sludge liquors, thereby increasing salt concentrations in the leachate. Net precipitation increases both the hydraulic head on a pond and the incidence of landfill infiltration by rainwater. Engineering solutions are available for each of these problems.

Wind Erosion--

The second effect of local meteorological conditions is caused by surface wind erosion. If the disposal site dries out and is not supporting vegetative cover, wind can erode the surface material and remove it from the site. The importance of this phenomenon will vary from area to area. Wind erosion can be prevented by stabilizing the surface of the material. Effective engineering solutions must aim at surface stabilization.

Even so, stabilization processes are not altogether effective at reducing wind erosion potential. Studies by WES (Ref. 104) have shown that some stabilized sludges break down to some extent under wet-dry and freeze-thaw cycling. While this may only be a surface effect in a deep landfill, it nonetheless presents a possible wind erosion problem. This has occurred at the Duquesne Light Company Phillips Station, where a series of hot, dry summers has resulted in substantial fugitive dust emissions from the compacted surface of the stable landfill. An extensive sprinkler system has been installed surrounding the site for use during dry, windy conditions (Ref. 142).

Covering a site with topsoil or using similar techniques which allow establishment of a vegetative cover will help stabilize the site, as is doen with dry ash disposal. Observations of fly ash disposal sites located in the southwest areas of the United States indicate that the surface can also be stabilized by bottom ash. When both fly ash and bottom ash are disposed of at the same site, the wind erodes the loose fly ash from between themixture of fly and bottom ash, leaving a surface covered only by bottom ash. Bottom ash particles tend to be too large for wind erosion. Once this bottom ash surface is formed, the site is stabilized against further wind erosion. Engineering solutions are therefore available for the wind erosion problem at FGD sludge lnadfills. The proper selection of cover materials is certainly preferable to sprinklers and other dust control methods due to limited maintenance. Several sludge disposal systems have adopted co-disposal of fly ash, bottom ash, and sludge and found that the surface stabilizers help (see SEction VII). Since bottom ash mixtures need cover only the top few feet of the site to prevent erosion, it can be added before the site is closed.

HEALTH EFFECTS

The dissolved salts, trace metals, and other contaminants contained in FGD sludges are all found in man's natural environment. Through evolution man has acquired a tolerance for these contaminants and requires many of them in his diet for good health. A typical biological response curve would show an increasingly beneficial effect with increasing contaminant concentrations up to a certain optimum level. Beyond this level there is a tolerance region beyond which benefits decrease, injurious effects begin, and finally a lethal concentration is reached. The goal of FGD sludge management is not to reduce contaminant levels to zero but rather to ensure that the concentrations of the contaminants which could eventually return to man and other biota are not at harmful levels.

The purpose of this section is to put the health effects of FGC sludge contaminants in perspective by identifying (1) the possible contaminant pathways to man, and (2) the potential contaminant concentrations at the point of consumption or exposure. Related information is contained in Section VI which discusses the range of contaminant concentrations in the liquid phase of FGC sludges, and in Section XI which discusses drinking-water quality standards.

Contaminant Pathways

The potential health problems posed by sludge disposal can be approached by examining contaminant pathways to man in Figure 19. It can be seen that adding an FGC system to a power plant effectively removes trace contaminants from the atmospheric pathway to man and places the contaminants instead into drinking water. This converts a regional atmospheric pollution problem into a potential local water pollution problem.

Groundwater--

The major potential pollution problem in FGC sludge disposal is the transport of leachate contaminants from the disposal site into local potable groundwater supplies. Predicting the potential mass transport of specific contaminants to man via this pathway is complex and involves the following major variables:

- The flow rate of the leachate from the disposal site into the aquifer, which is dependent upon such factors as permeability of the soils and liner (if any) underlying the disposal site, and the hydrostatic head force upon the leachate;
- The concentration of the specific contaminants contained in the leachate generated by the disposal site, and the changes occurring in these concentrations due to attenuation effects by the soil during passage of the leachate to the aquifer;
- The capability of the aquifer through actual replenishment to dilute the leachate reaching it, i.e., the

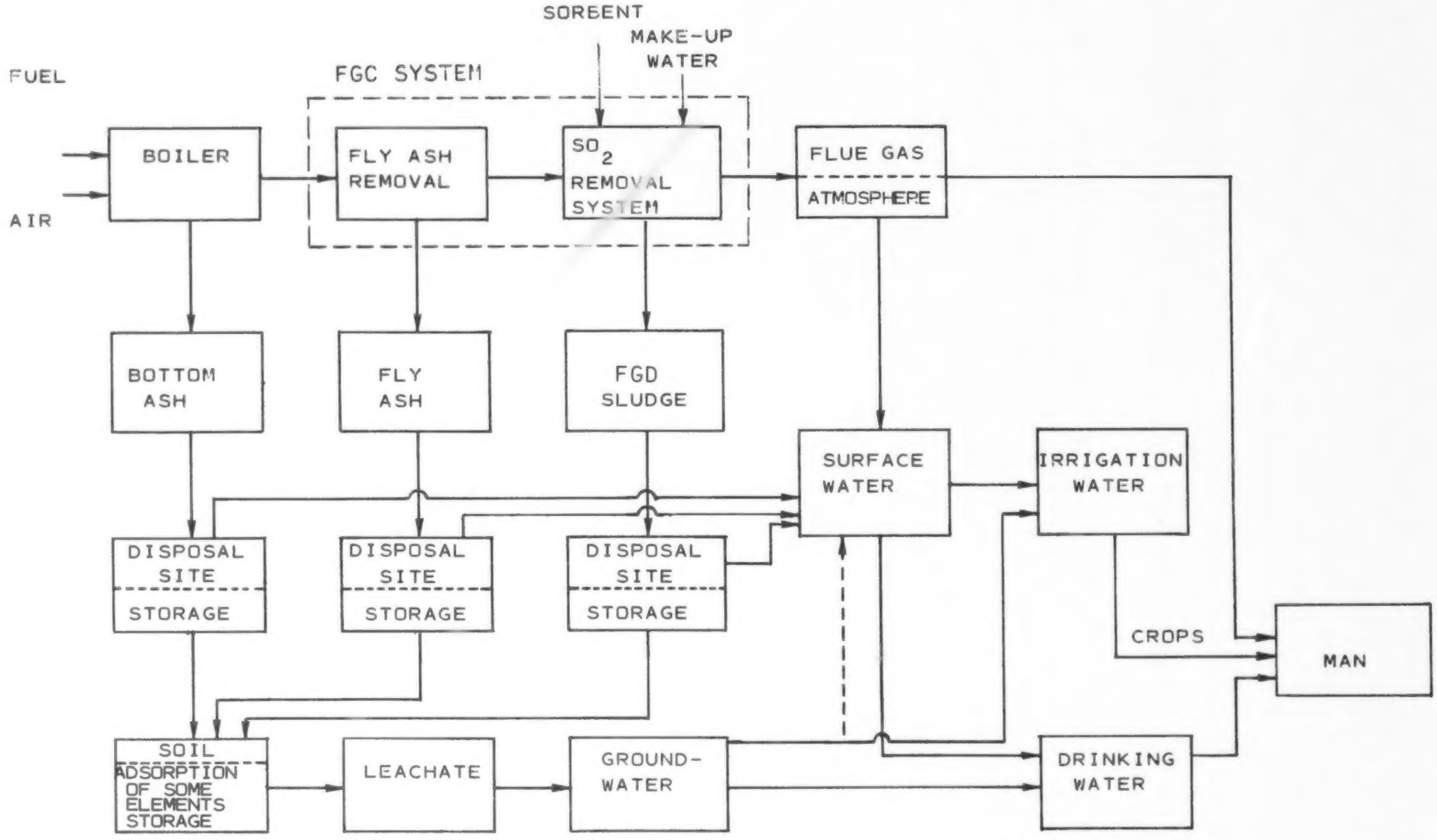
SORBENT
MAKE-UP WATER
FUEL
AIR
FGC SYSTEM
BOILER
FLY ASH REMOVAL
SO2 REMOVAL SYSTEM
FLUE GAS
ATMOSPHERE
BOTTOM ASH
FLY ASH
FGD SLUDGE
SURFACE WATER
IRRIGATION WATER
DISPOSAL SITE
STORAGE
DISPOSAL SITE
STORAGE
DISPOSAL SITE
STORAGE
CROPS
MAN
SOIL
ADSORPTION OF SOME ELEMENTS STORAGE
LEACHATE
GROUND-WATER
DRINKING WATER

Figure 19. Simplified pathway chart for contaminants in coal reaching man.

relative volumetric rate of (1) the leachate reaching the aquifer, (2) the replenishment by natural sources such as horizontal groundwater migration, (3) the rate of water supply withdrawal, and finally (4) the extent of the mixing which occurs in the aquifer between leachate and natural source water; and

- The contaminant concentrations of the natural source water in the aquifer and their relation to concentrations of similar contaminants in the leachate reaching the aquifer.

The above listed variables are often interrelated, complex, and difficult to measure accurately. Considering, however, the large size and costs involved in FGD sludge treatment and disposal, the effort to evaluate these factors should be cost effective in designing the best sludge management system for a particular site. It is outside the scope of this report to delve comprehensively into each variable potentially effecting health effects. However, a brief discussion follows.

Two storage functions are shown in Figure 19. The first of these is associated with the storage capability of FGD sludge itself after ultimate disposal. Several of the contaminants of interest are either coprecipitated with the sludge crystals or contained in the fly ash. As a result, they are retained indefinitely within the disposal site. For chemically stabilized sludges, new solid phases are created which often immobilize impurities which would normally be in the liquid phase.

Another part of the site storage function is a delaying action created by artificial or natural low permeability liners underlying the disposal site. The long-term effectiveness of various liners is being tested. However, it is possible that most liners will eventually deteriorate or be bypassed. Therefore, on a geological time scale such storage is temporary and control over the rate of release of contaminants is the major advantage.

A second storage function is associated with the soil system. As contaminants are leached from the disposal site, they can be retained by the soil. At least three mechanisms are involved. One mechanism involves the precipitation of some of the contaminants. A second storage mechanism involves ion exchange within the soil. Soils which are high in organic and clay contents have considerable cation exchange capability, as well as limited anion exchange capability. Physical adsorption of the impurities on the surfaces of the soil particles is a third mechanism delaying their migration. Most elemental contaminants are readily adsorbed by soils. Of those contaminants found in the sludge, only fluoride, boron, chloride, selenium, and arsenic are not easily absorbed by most soils, due to their anionic nature.

The soil/groundwater system provides a delaying action for contaminant release. In the process, the system limits the concentration of impurities in the aquifers. The actual delay time associated with the system depends upon the chemistry of both soils and leachate, and the associated liquid flow rate. Even in soils with relatively high permeabilities, it is possible that certain contaminants may migrate only a few feet over a period of centuries. For contaminants which are not readily absorbed by the soil, the storage times may be very short.

Contaminant concentrations which may reach man are influenced by these storage times. When the storage time is substantially greater than the useful life of the power plant and its sludge disposal system, the storage system reduces the rate of release of contaminants to a level where their addition to the groundwater system may be of little or no consequence to human health. When the storage time for a given contaminant is short in comparison to the life of the facility, the contaminant will enter the groundwater system at or near its original concentration and be quickly dispersed. The proper selection of a storage function, provided by either FGD sludge or the soil/groundwater system, can control the rate of release of contaminants to an environmentally acceptable level.

Surface Waters--

A second pathway by which contaminants contained in FGD sludge may reach man is by way of surface waters. In this case, pond supernatant enters a nearby water course, which in turn is used as a drinking water supply. Considering the initial concentrations of the contaminants in question and the dilution capabilities of the surface waters adjacent to many power plants, the levels of contaminant reaching man from this source will be strongly site-specific. However, good engineering practice can render this practically nil.

Atmosphere--

The atmosphere provides a third pathway by which these contaminants may reach man. Even those power plants equipped with FGD systems and high efficiency particulate removal do not collect all contaminants. Once in the atmosphere, these contaminants will be inhaled by living beings or deposited on the local terrain. Pollutants which settle out may reach man through food crops or surface water runoff to drinking water supplies. Atmospheric dispersion results in a lower concentration of contaminants. As a consequence of this dispersion, surface waters and soil concentrations would therefore also be lower.

Health Significance of Sludge Contaminants

The health effects of metals and their compounds are often difficult to quantify. Some are necessary to life in small concentrations but toxic at high concentrations. Others react differently within the body depending upon the chemical state.

Of the heavy metals found in FGC sludge, five elements (arsenic, lead, mercury, fluoride and selenium) represent known hazards to human health, based on existing evidence. Lead, mercury, and cadmium are particularly insidious because they can be retained in the body for relatively long periods of time, thus functioning as cumulative poisons (Ref. 145).

Table 33 provides a comprehensive summary of the presence of metals in the environment, their toxicity to humans, and their half life in the body. As can be seen from the table, the most toxic of these metals are antimony, arsenic, cadmium, lead and mercuric salts.

In the liquid phase, trace element concentrations are important in determining the potential health hazards of leaching or of surface water discharge. Since each of these studies involved different power plants, results are not directly comparable. A summary of these concentration ranges is given in Table 34. This table includes trace contaminants which are considered important to health or the ecology.

The range of data shown in the table for sludge leachates/ elutriates represents a wide variety of power plants and scrubber systems. While the data do not always agree between sources, virtually every drinking water standard is exceeded by at least one sample value between the three sources.

More importantly, further analyses of these data indicate that only a few parameters consistently exceed drinking water standards (i.e., the standard value falls just inside or outside the lower end of the sample range). These parameters are TDS, arsenic, lead, mercury, fluoride, and selenium. Their potential effects are discussed below.

Total Dissolved Solids--

The TDS concentration of FGD sludge has in some instances been as high as 95,000 mg/ (Ref. 104). The amount of TDS depends primarily upon the mode of scrubber operation. For example, if the scrubber is operated in a very tight, closed-loop mode, the soluble salt concentration will accumulate to a much higher level than that experienced in a more open-loop operation. Double alkali sludge liquors may contain large quantities of dissolved solids, depending upon the effectiveness of the sludge cake washing techniques employed. Insufficient

TABLE 33. METALS IN THE ENVIRONMENT AND THEIR TOXICITY*

Metal	Average daily intake ($\mu g/d$)		Oral dose producing	Fatal dose	Total body content	Whole body half-life
	Food and Water	Air	toxicity (mg)	(ingestion)	(mg)	(days)
Antimony	100	1.7	100	100-200 mg	7.9	38
Arsenic	400-900	--	5-50	120 mg	15-20	280
Barium	735	30	200	1 g	22	65
Beryllium	12	0.04	--	not known	0.3	180
Cadmium	160	7.4	3	not known	50	200
Chromium	245	1.1	200	5 g	1.8	616
Copper	1,325	11.4	50-250	10 g[b]	72	80
Iron	15,000	84	--	5-10 g[c]	4,200	800
Lead	300	46	--	0.5 g	120	1,460
Manganese	4,400	28.8	not known	--	12	17
Mercury	25	--	--	20 mg - 1 g[d]	--	70[e]
Nickel	600	2.36	--	--	10	667
Selenium	62	--	5	--	14.6	11
Silver	60-80	--	60	2 g[f]	1	5
Tin	7,300	0.6	2,000	--	17	35
Zinc	14,500	16.8	--	10 g[g]	2,300	933

* Ref. 145

[b] Copper sulfate

[c] A two-yr old child

[d] Mercuric salts

[e] Methyl mercury

[f] Silver nitrate

[g] Zinc/sulfate

TABLE 34. SUMMARY OF LEACHATE DATA FROM SEVERAL STUDIES OF FGD SLUDGE CHEMISTRY

		Range in Liquids mg/l			Frame of Reference Values					
Element or Item	Range in solid sludge mg/kg	FGD Sludge Leachate Ref. 12	FGD SLudge Leachate Ref. 131	FGD Sludge Elutriate Ref. 101	Fly Ash Solids mg/kg Ref. 131	Coal Ash Leachate mg/l Ref.	Primary Drinking Water Standards Ref.	Sanitary Waste Effluent mg/l Ref.	Landfill Leachate mg/l Ref.	Soils mg/kg Ref. 93
TDS	--	3200-15,000	--	2,600-7,000	--	2,200	500	--	1,500-9,200	--
pH	--	3.04-10.7	8.4-9.7	--	--	13	--	--	--	--
As	4-15	.004-.3	<.002-.03	.006-.019	3.2-74	<.002-.084	.05	.013	--	--
Ba	<20-4,400	--	<.3-2	--	700-15,000	<.3-40	1.0	--	--	--
Be	1.5-4.0	.002-14	.001-.002	.0005-.01	5.2-13	.0006-.003	--	--	--	--
B	41-210	8.0-46	.96-6.3	--	179-1040	.03-17	--	--	--	--
Cd	.4-25	.004-.11	.0005-.002	.014-.032	.39-5.3	<.001-.0025	.01	.013-.2	.007-.05	.01-7
Cr	1.6-15	.01-.5	<.001-.011	.002-.08	3.6-28	<.001-.21	.05	--	.053-.33	--
Cu	39-104	.002-.2	<.005-.045	.004-.3	43-238	<.005-.092	1.0	.08	.17-.45	2-100
F	260-1017	.07-10	7.6-31.5	--	84-2880	1.4-17.3	1.4-2.4	--	--	--
Ge	<.1-6	--	<.01-.02	--	1.2-25	<.01	--	--	--	--
Hg	<.01-2	.0004-.07	.0005-.001	.01-.03	<.01-.146	.0003-.015	.002	.002	.003-.03	--
Pb	1-290	.01-.4	.003-.006	.0029-.06	4-27	.0027-.024	.05	.08	.09-.29	2-200
Mn	56-340	.09-2.5	<.002	.01-9.0	157-374	<.002	.05	--	--	100-4000
Mo	8-81	.91-6.3	.006-.007	--	6-12	.01-.7	--	--	--	--
Ni	<12-75	.05-1.5	<.05	.007-.03	34-108	.015-.05	--	--	--	10-1000
Se	2-18	.001-2.2	.01-.045	.005-.13	1.7-16.4	<.0005-.47	.01	--	.02-.077	--
Sb	4.3-7.5	--	.013-.035	--	1.-4.4	.006-.033	--	--	--	--
V	<100	.001-.67	<0.1	--	<100	<.1	--	--	--	--
Zn	14-2,000	.01-.35	.005-.045	.024-.88	92-854	<.005-.038	5.0	.23	--	10-300

washing can result in significant sodium, potassium, or other salt concentrations in the sludge liquor.

Ionic species typically contained in the leachate are sodium, calcium chloride, sulfate, and limited amounts of sulfite (due to low solubility). The calcium component of TDS can be absorbed by the soils, but mass balance and conservation of charge relationships require the release of some other cation presently contained in the soils, normally sodium. The absorption of the soils will tend to shift the sodium/calcium ratio, although the total number of equivalents per liter would remain relatively constant. If the leachate is to meet the potable water standard for TDS (500 mg/ℓ), the required dilution would ordinarily be 4:1 to 30:1.

Arsenic--

The fatal dose of arsenic is 0.1 to 0.3 g. Organic arsenicals, such as arsphenamine and dimethylarsinic acid, release slowly and are therefore less likely to cause acute poisoning. The manifestations of arsenic poisoning appear to vary with ethnic background, with blackfoot disease, pulmonary disease, and gastrointestinal disturbances predominating. The principal arsenic poisoning is hemolysis.

Arsenic presumably causes toxicity by combining with sulfhydryl (-SH) enzymes and interfering with cellular metabolism. Arsenic is suspected to be a carcinogen but not tumorigenic. Arsenic was also suspected to be associated with increased incidence of hyperkeratosis and skin cancer when arsenic-contaminated water (0.3 mg/ℓ) was consumed. Chronic exposure to arsenic in drinking water (2.2 mg/ℓ) was reported to cause gangrene of the lower limbs (Ref. 145).

Table 34 shows that typical arsenic concentrations in FGD sludge leachate are well below drinking water standards. Only at one location were leachate arsenic levels at or near the 0.5 mg/ℓ standard (Ref. 12). Considering the possible forms of arsenic and the attenuation/dilution potential at the site, arsenic contamination of surrounding waters should not present a significant health problem.

Lead--

Although lead is a cumulative poison, not all of it is absorbed or retained by the body. Most of it is absorbed into the blood and later excreted in the urine so that blood lead does not rise to acute levels, except in cases of prolonged exposure at high concentrations. A small portion of this daily lead intake gradually accumulates in bones where it is normally insoluble and harmless. But under certain conditions, such as periods of high calcium metabolism in feverish illness, cortisone therapy, and old age, this accumulated lead can be released suddenly into the blood at toxic levels.

American citizens have the highest average blood levels of lead in the world. Although these blood levels are significant, they fall well below the toxic threshold level for classical lead poisoning. Because the general population is already exposed to dangerously high levels of lead through food and air, however, lead levels in water should be kept at a minimum.

Up to 100 cases of lead poisoning, with an average of ten fatalities, are reported yearly. Most of these fatalities are in children who lived in homes built before 1940 and can be traced to lead based paint. Seven cases of lead poisoning from drinking water in Australia in 1973 were reported. The well water they used contained a soluble lead content of about 14 mg/ℓ (Ref. 145).

Lead levels are typically well below the drinking water standard of 0.05 mg/ℓ in FGD sludge leachate. Only the Aerospace analyses at Shawnee (Ref. 12) have shown lead concentrations at or above the standard. As lead is readily attenuated in soils with any ion exchange capacity, contamination of groundwaters by lead contained in FGD sludge leachates is not expected to be a problem.

Mercury--

The fatal dose of mercuric salts is 20 mg to 1 g. The biological half-life of inorganic mercury compounds is estimated to be about 70 (30 to 100) days. Ingested metallic mercury is not toxic since it is not absorbed. Mercurous chloride and organic mercurials such as acetomeroctol, ammoniated mercury, merbromin, mercocresol, and mercury protoiodide are not likely to cause acute poisoning because they also are poorly absorbed. The single fatal dose of these compounds is three to five times the fatal dose of soluble mercury salts. The mercurial diuretics (mersalyl, meralluvide, mercurophylline, mercumatilin, mercaptomerin, chlormerodrin, and merethoxylline) are almost as toxic as mercury salts. Volatile diethyl and dimethyl mercury are ten times as toxic as mercuric chloride (Ref. 145). It is therefore crucial to determine the chemical forms of mercury in the leachate when evaluating potential health effects.

Since the leachates under consideration generally contain both sulfite and sulfate ions in solution, a well-defined oxidation/reduction potential exists. Thermodynamic calculations based upon realistic SO_3/SO_4 ratios indicate that the mercury will exist in one of the reduced states, either as elemental mercury or possible mercurous chloride. In these insoluble forms the mercury mobility and the potential for consequent deleterious health effects are reduced.

However if disposal site characteristics vary from those favoring the existence of insoluble forms of mercury (such as increased oxidation potential or acid leachate), soluble mercury compounds would be formed. Mercury, when exposed to anaerobic aquatic environments also methylates, thereby becoming even more toxic.

The high attenuation capacity of most soil for mercury coupled with the typically high pH of most FGD sludges would seem to relegate mercury to a non-critical status at the leachate concentrations shown. Nonetheless, this attenuation capacity is a site characteristic; this capacity should be documented for each site before mercury can be dismissed from being a potential hazard.

Fluoride--

Fluorides are not considered toxic at even the highest concentrations found in FGD sludge liquors. While several studies have not analyzed the fluoride concentration in sludges, the high fluoride content indicated by certain of the EPRI/Radian Corporation data (Ref. 134) would cause severe mottling of children's teeth. The amount of fluoride necessary to cause this mottling is indicated in Table 35.

Fluorides, like many other anionic species, are not attenuated in most soils. Because fluorine is beneficial to man at the concentrations noted in most of the leachate samples shown, fluorine may not be a problem when dilution and other site characteristics are taken into account. Fluoride migration in leachate occurs in much the same fashion as TDS and can therefore be correlated with TDS monitoring results (see Section IX).

Selenium--

Recent measurements indicate that selenium emissions from the burning of coal account for 62 percent of total industrial emissions of selenium in relation to natural sources (Ref. 22). Both selenium-deficient and selenium-rich areas exist in the United States and throughout the world. Selenium in low concentrations is beneficial and in high concentrations is a toxicant. In regions deficient in selenium the propensity of organismal bioaccumulation will be greater than in regions where selenium is prevalent. The only reported case of human selenium toxicity from water supplies was the result of a three-month exposure to well water containing 9 mg/ℓ (Ref. 145). This level is higher than that found in the worst sludge leachate by more than an order of magnitude.

Selenium enters the FGC system in the form of elemental selenium. The existence of sulfite in the sludge will affect the oxidation reduction potential, preventing oxidation of

TABLE 35. EFFECT OF INCREASED CONCENTRATIONS OF FLUORINE IN DRINKING WATER ON TEETH*

<1.0 mg/l	Increased possibility for dental caries
1 mg/l	Optimum concentration for dental health
1.7 mg/l	Mottling in 40 to 50% of the children
2.5 mg/l	Mottling in 80% of the children; one-fourth of which are severe
4.6 mg/l	100% mottling with a marked increase in severity

---

* Ref. 55

selenium to a more soluble form, selenite (SeO_2^{-2}) or selenate (SeO_4^{-2}). These forms are uptaken by organisms (Ref. 22). Selenium occurring as inorganic selenides or in the elemental form is very insoluble and not readily absorbed (Ref. 22).

The current USEPA drinking water standard for selenium is 0.01 mg/ℓ. In virtually every case, FGD sludge liquor selenium concentrations were shown to exceed this standard (typically by a factor of 1 to 4). As selenium is an anion and behaves much like fluoride in passing through soils, this parameter is one which needs to be controlled during disposal.

Summary--

The following conclusions can be made regarding the health significance of leachate and surface water discharges from disposal systems:

- All studies agree that the total dissolved solids in the sludge liquors exceed drinking water standards;
- All studies indicate that the selenium concentration commonly exceeds drinking water standards;
- The EPRI/Radian data indicate that in some instances fluoride concentrations may be high;
- All studies indicate that arsenic, lead, and mercury (among others) can exceed drinking water standards in some instances, although typically below standards and readily attenuated by most soils.

SAFETY

Safety considerations associated with the disposal of FGC sludges can be directed toward three groups: (a) workers employed at the site; (b) the general public; and (c) livestock and wild animals. These safety considerations relate to the physical rather than the chemical properties of the sludge.

The safety of the workers at the plant is determined by their awareness of the potential dangers associated with the disposal site and material handling equipment. Each safety hazard is specific to the plant in question; at present, the safety of the materials handling equipment and operating procedures is regulated by OSHA and MESA guidelines (see Section XI).

The thixotropic nature of certain FGD sludges poses an unusual safety hazard. A pond filled with such material may develop an apparently solid surface crust. This crust, however, may liquify on impact (such as a person jumping or a vehicle braking on the surface). Whether liquification will threaten men or machinery will depend upon the thickness of the crust. Certain other industrial wastes, such as drilling muds, also exhibit this property.

The answer to the safety problems associated with the sludge disposal area lies in worker awareness of the associated hazards. This is best achieved through the development and implementation of standard safety procedures. These procedures should include the use of a lifeline if onw person is attempting to work on a dried pond, as well as appropriate warning signs and barriers in plant and disposal areas.

Stabilized sludges are more structurally sound than raw sludge and are not thixotropic in nature. The safety hazards are therefore reduced to those of conventional materials handling and heavy equipment operation. It should be noted that some of the stabilizing additives are caustic and must be handled carefully.

The safety hazards to the general public are also a factor of the load supporting characteristics of the sludge. Potential dangers can be averted by fencing the site and by posting appropriate warning signs.

The dangers to animals and livestock is also determined by the load supporting properties of raw sludge. Limiting access is the best defense against this problem. In dry areas, wild animals and livestock may be tempted to cross a crusted pond to reach the wet area for drinking water. Once the animal becomes mired in the material, his chances of escape would be minimal unless aided by man.

ECOLOGICAL CONSIDERATIONS

FGD sludge disposal operations have potential for adverse impact on the surrounding ecosystem. Of primary concern are:

- The aquatic environment;
- The terrestrial environment;
- Irrigated agriculture and livestock.

This discussion will evaluate the accessibility of FGD sludge and its contaminants to the above listed ecosystems.

Aquatic Environment

Sludge disposal may affect the aquatic environment through either accidental release to a waterway or through intentional discharge to surface or groundwater. Surface and groundwater discharge is generally continuous; accidental discharge is a random, possibly catastrophic event.

Catastrophic Events--

Figure 20 illustrates the change in the sludge contaminant pathway due to catastrophic sludge release. Since large volumes of cooling water are required to operate a fossil fuel-fired power plant, most plants are located near a large body of water. Installation of FGD units on these power plants entails a large number of pipes to carry the slurries around the scrubber and associated materials handling systems. Pipelines also usually carry the sludge to disposal areas. Depending upon system design, a pipeline break could result in the accidental discharge of the slurry into a watercourse. Dike failure at a disposal pond may release several years' supply of sludge into a waterway in only a few hours, producing a truly devastating event.

Pipe failure--The consequences of a major pipe failure can be suggested by outlining the effects of accidental sludge release into a major river with a flow rate of approximately 5,000 cfs. This flow rate is comparable to that of the Colorado River as it flows across Colorado/Utah border. The solubility of oxygen in water is on the order of 7 ppm; the river would be transporting roughly 1 kg/sec of oxygen past any particular point. A 1,000 megawatt power plant using 3 percent sulfur fuel with an 85 percent FGD efficiency would produce 7.5 kg/sec of calcium sulfite hemihydrite, or approximately .93 lbs/sec of COD. Under these conditions, a sludge released into the adjacent river during a pipeline failure would effectively absorb all the oxygen in the water, and kill all aquatic life in the vicinity.

The impact on aquatic life forms from suspended solids will vary but are experted to be minimal. The flow rates characteristic of such a pipe break are relatively small in comparison to the total flow rate of the river. Most aquatic organisms can endure relatively high concentrations of suspended solids for short periods of time. Fish are able to clear their gills of suspended sediments, but this requires metabolic energy and stresses the fish. This is usually not fatal until suspended solids levels exceed several thousand ppm. In the case of a pipe break, from 10 to 100 ppm suspended solids could be expected depending on the amount of ash contained in the sludge.

The site-specific nature of any accident requires that each plant and its associated water course be individually evaluated. Estimations of potential hazards should include the flow rate of the river, the potential oxygen transfer capabilities of the river system, and the probably flow rates and sulfite content of the sludges in question. The severity of an accidental sludge discharge from pipe failure may be reduced if:

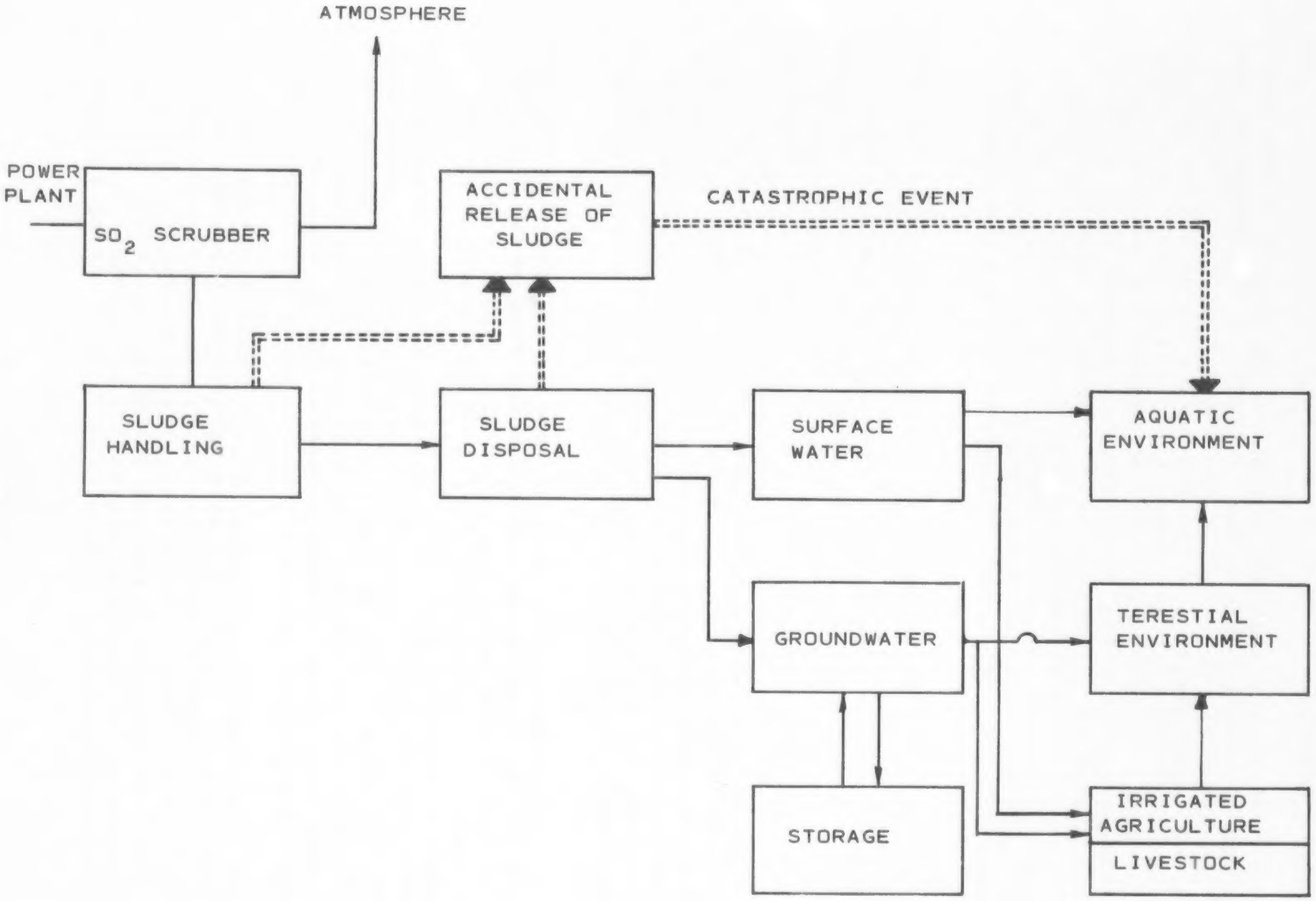
ATMOSPHERE
POWER PLANT
SO2 SCRUBBER
ACCIDENTAL RELEASE OF SLUDGE
CATASTROPHIC EVENT
SLUDGE HANDLING
SLUDGE DISPOSAL
SURFACE WATER
AQUATIC ENVIRONMENT
GROUNDWATER
TERESTIAL ENVIRONMENT
STORAGE
IRRIGATED AGRICULTURE
LIVESTOCK

Figure 20. Comparison of FGD sludge contaminant pathways to the environment.

- The water velocity is sufficiently low to permit rapid settling of the calcium sulfite crystals;
- The river flow is non-uniform, so that there are pockets in the river where the fish can escape the reduced oxyten conditions;
- The calcium sulfite crystals through the water column are more highly concentrated at the bottom, with very low concentrations at the surface; this provides a thin layer of surface water where the fish can survive.

When estimating the effects of pipeline breaks, it should be noted that the required oxygen levels for fish vary according to species. The more sensitive species, trout and salmon, require oxygen levels about 5 ppm; severe metabolic stress is experienced below 4 ppm. Some of the more hearty warm water species such as carp, can survive in as little as 2 ppm oxygen.

Fish are capable of searching for high oxygen areas when they are being stressed by a low oxygen environment. Even bottom-dwelling fish such as catfish may be seen at the surface of water bodies whenever the oxygen level drops below 4 mg/ .

In a fash-flowing river maintaining undissolved calcium sulfite in suspension, oxygen depletion might extend many miles downstream from the point of discharge before reaeration from the atmosphere could oxidize all the sulfite to sulfate and reoxygenate the water. A smaller river or stream would, of course, be more severely impacted.

The potential impact of the accidental release of sulfite sludge into a water course can also be estimated by examining oxygen depletion in rivers receiving sanitary waste. In terms of oxygen depletion, an accidental sludge discharge from a 1,000 megawatt power plant would have roughly the same effects as the discharge directly into a watercourse of raw sanitary waste from a city of about 300,000 people. In other words, an accidental FGD sludge spill will have about the same impact on the oxygen levels of a receiving water as the discharge into the same waterway of untreated municipal waste from one third of the population being served by that power plant.

Dike failure--If sludge is disposed of in ponds the possibility of dike failure and spill into surface waters exists whenever the elevation of the pond is greater than that of the local watercourse. Kike failure of FGD sludge disposal ponds has not yet occurred. However, dikes have failed in ponds containing other waste materials, such as acid mine drainage sludge and phosphate slimes.

Dikes can fail for a number of reasons. Many signs of impending failure have unique visible characteristics which can aid in diagnosis. These include rotational slips, surface slips, and flow type slides in addition to other slope movements such as creep and backsapping (a concentrated areas of erosion which continues to progress up the slope, the product of an intermittent flow of water on the downstream face).

General factors affecting embankment stability include:

- Size factors: height, width, volume;
- Slope steepness;
- Slumping, sloughing, sliding (superficial or deepseated);
- Cracks parallel to the embankment crest or to stream direction;
- Seepage: location, volume, carrying solids;
- Freeboard;
- Soils and downstream tow area;
- Bank erosion;
- Embankment vegetation;
- Phreatic surface.

These factors are related to the materials, methods of dike construction, and the types of underlying soils.

Accidental release of FGD sludge would produce an immediate physical impact on an adjacent watercourse. Once the sludge wave had dissipated, the total suspended solids and chemical oxygen demand would continue to devastate the surrounding area. The total suspended solids loading would wither smother or bury aquatic life forms until sufficient percentage of the material had settled out. Beyond that point, the remaining suspended solids (10,000 to 100,000 ppm) would continue to absorb oxygen from the water. As long as the flow velocity was fast enough to maintain the remaining material in suspension, all aerobic aquatic life forms would suffocate. This action would last until the calcium sulfite crystals settled out or oxygen demand was satisfied. As long as calcium sulfite existed in large quantities on the river bottom, an increase in flow velocity could stir it up. Resuspended, it could exert an oxygen demand on the entire water column. As a result, it could be very difficult to successfully stock a river with fish for a long time after such an event.

It is estimated that the COD in one 300 hectare-meter sulfite sludge pond would be sufficient to remove all the dissolved oxygen from virtually any lake or several hundred miles of a large river. However, in a lake-type environment, rapid settling of the sludge would limit the impact to that of the immediate area of discharge.

Considering the number of dikes and ponds in use and the comprehensive regulations governing their construction, the probability of dike failure is low. Should such accidents occur, however, the environmental consequences could be severe.

Surface and Groundwater Discharges--

In addition to accidental discharges to surface waters, water from an FGD sludge pond can enter the aquatic environment through (1) an intentional direct discharge to surface waters or (2) percolation of pond water through underlying soils to groundwater supplies. The possibility of a direct surface discharge depends upon details of disposal site design. At this time, no existing FGD system discharges pond water to surface waters on a continuous basis; they are currently all designed to produce no direct discharge. Percolation rates will depend upon local site characteristics and disposal techniques.

Important discharge charcteristics include the concentrations of total dissolved solids and trace contaminants.

Relatively small flow rates are involved. Flow rates from an SO_2 scrubber are generally more than an order of magnitude less than the discharge flow rates from a cooling tower. At once-through cooling plants, the cooling water dominates all flows in the facility. Therefore, considering the total flow rate in most power plants, any surface water discharge could be diluted by other plant flows.

Although sludge liquors may contain as much as 15,000 ppm TDS, many fresh water fish commonly found in the United States could easily tolerate these conditions. Adronomous species of fish are able to tolerate salt concentrations several orders of magnitude greater than that of typical sludge liquors. Trout, for example, can tolerate the salinity of full strength seawater, or 3.5 percent TDS. Most aquatic plants are equally tolerant of slat concentrations up to several thousand ppm. It seems likely, then, that high dissolved solids concentrations will have a minimal effect on aquatic life forms.

Specific elemental contaminants contained in the sludge might have some impact on the aquatic ecology. In general, the heavy metal tolerance of fish increases with TDS tolerance. The metal of primary concern is mercury. Mercury has certain special properties; in the leachate entering surface water supplies it may be absorbed by the sediments in the water body. Bacteria in the sediments convert elemental mercury or other insoluble mercury compounds to methyl mercury, the most toxic form of mercury. Moreover, as a consequence of its nonpolar nature, it can accumulate in the biological system.

In summary, the low concentrations of most trace metals in FGD sludge leachate would not appear to present a problem to nearby aquatic life forms through groundwater discharge. Direct exposure to the TDS levels present in sludge leachate could harm certain aquatic life forms. Accidental release of sludge to surface waters could suffocate nearby aquatic life and stress fish life due to the expected high levels of suspended solids.

Irrigated Agricultural Considerations

When estimating the potential impact of FGD sludge leachate or liquor on irrigated agriculture, the most important contaminants are TDS, selenium, and boron. None of these is readily absorbed by soils. These contaminants can therefore enter the ground or surface waters. After leaving the site, these impurities may enter an irrigation system. The adverse impact of these components on agricultural lands is documented. A high TDS concentration in irrigation water requires modification of irrigation practices in order to prevent high salinity in the root zone of the plants. The impact of saline irrigation on crop yields has been extensively studied, particularly in the southwestern U.S., where the problem is most prevalent.

The effects of salinity on various crops grown in the southwest are shown in Figure 21. This figure includes the range of values found in typical FGD sludge liquor, and shows that it would be unreasonable to use the undiluted liquors for irrigation on a majority of crops.

The salt loading by irrigated agriculture in the upper Colorado basin can be compared to the total potential salt loading of all flue gas desulfurization systems installed by 1985. If all of these FGD systems were to utilize unlined ponds, and had an underlying soil permeability on the order of 10^{-6}, the total salt loading from FGD pond leachate by 1985 would still comprise only an insignificant amount of the salt loading contributed at present by irrigated agriculture in the upper Colorado basin (Ref. 170).

Boron is also of concern to irrigated agriculture. Different crops have different sensitivities to boron in irrigation water and soil. The effects of boron on sensitive, semi-tolerant, and tolerant crops is shown in Table 36. A boron concentration of over 3.75 mg/ℓ is unsuitable even for the most tolerant crops. Boron concentrations in FGD sludge liquors range from 0.1 to 6.3 mg/ℓ . Leachates falling within the low

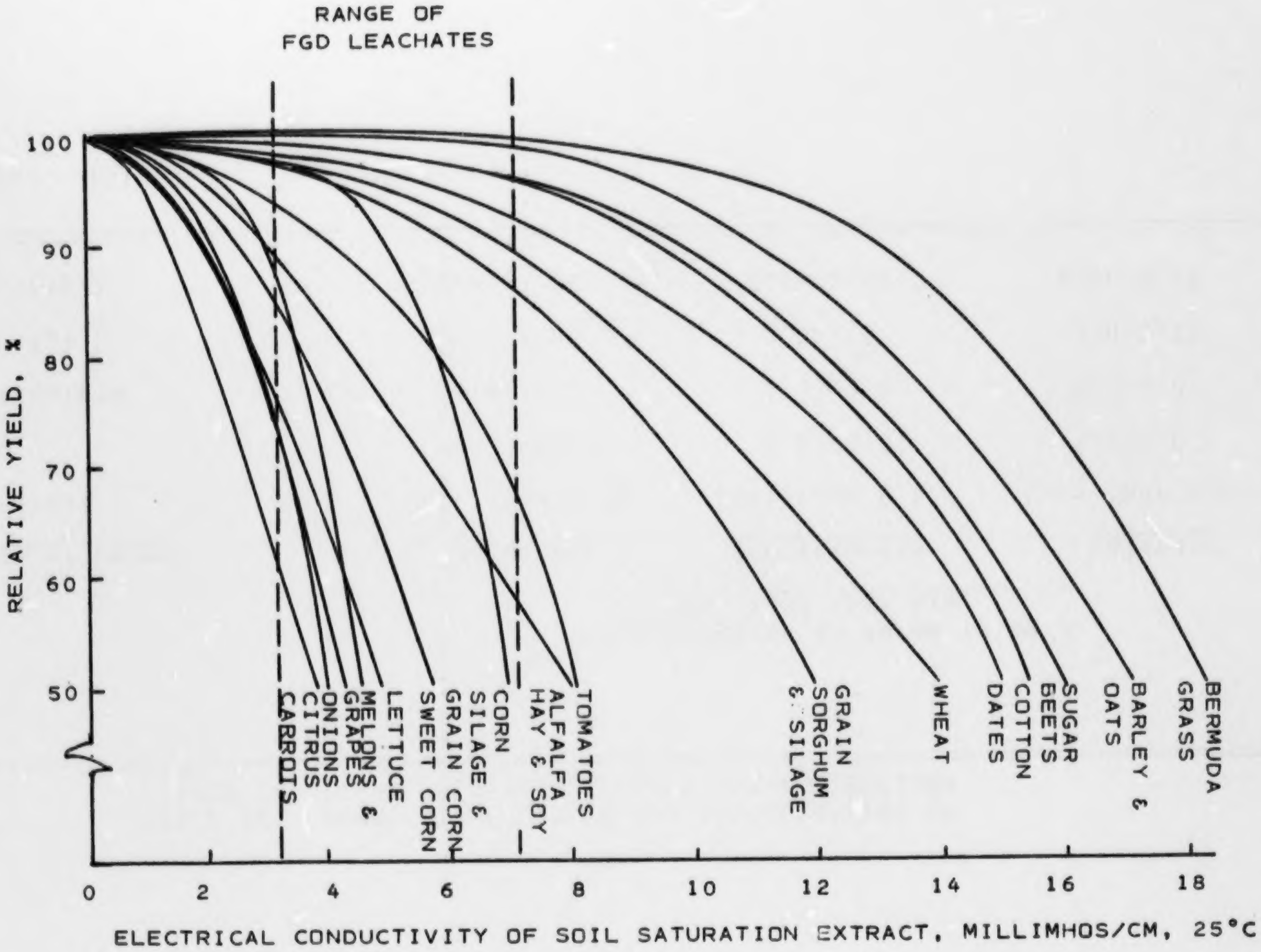

Figure 21. Salt tolerance of major crops grown in the Colorado River basin (Ref. 170)

TABLE 36. PERMISSIBLE LIMITS FOR CONCENTRATION OF BORON IN SEVERAL CLASSES OF WATER FOR IRRIGATION*

	Concentration of Boron in mg/ℓ for crops that are:		
Class of Water	Sensitive	Semitolerant	Tolerant
Excellent	Less than 0.33	Less than 0.67	Less than 1.0
Good	0.33-0.67	0.67-1.33	1.0-2.0
Permissible	0.67-1.0	1.33-2.0	2.0-3.0
Doubtful	1.0-1.25	2.0-2.5	3.0-3.75
Unsuitable	Over 1.25	Over 2.50	Over 3.75

* Ref. 101

end of this range would be acceptable for even the most sensitive crops. Concentrations of boron in the sludge itself can range from 41 to over 200 mg/ℓ , depending on the ash content of the sludge. Boron will be contained in the sludge for potential leaching over a very long period of time.

Selenium is a unique case, as was mentioned earlier in this chapter. Selenium can be a nutrient at low concentrations or a toxicant at high concentrations.

With the exceptions of selenium and boron, the other elemental contaminants contained in the liquid effluent and leachate from FGD sludge disposal systems are of no agricultural significance at the concentrations typical of FGD sludge leachate. In fact, studies are underway to investigate the use of dewatered sludge as a fertilizer additive of filler material in certain agricultural areas.

Livestock

The effects of FGC sludge liquor consumption on livestock could conceivably be a local problem under unusual circumstances. The salt tolerance limits of domestic livestock are specific to each animal, although generally between 3,000 to 12,000 ppm. As FGD sludge is ordinarily at the low end of this range, minimal dilution would render the leachate or supernatant harmless in terms of TDS.

The metals and toxic anions noted previously under Health Effects are equally important here. Metals such as lead and mercury are accumulated in animals and man alike, and could present a problem with livestock. The available chemical form of each element is important, but further investigation of speciation and effects on livestock is necessary.

Well water used for livestock consumption would probably be affected only by selenium and fluoride from FGD sludges. Mercury again would generally be absorbed by the soil before the leachate reached the well. Selenium would also be absorbed to some degree, but fluoride would migrate through the soil at approximately the same rate as the TDS.

Aesthetics and Land Use

The aesthetic impact of an FGD sludge disposal operation is strongly site-specific. Local variables include public proximity, appearance of the operation, and site reclamation potential. Untreated sludge ponds resemble other common ponding operations, e.g., ash ponds, sewage lagoons, raw water supplies, storage reservoirs, etc. Obviously, disposal site location, grading, landscaping, and access roads should be designed to minimize public view and proximity to this site.

The appearance of the disposal operation will also be affected by the mode of sludge transport and the treatment of small spills. Pipeline transport is a relatively clean operation. Truck, rail, and barge transport are likely to produce a certain amount of spillage during loading and transit. These problems can be minimized through selection of appropriate equipment and operating procedures.

After site decommissioning, cover material which will support vegetation should be considered. Revegetation to improve the appearance of a disposal site, however, may conflict with the design objective of minimizing leachate generation. Vegetation of a covered site will reduce the surface water runoff rate, permitting more water to percolate through the fill material into the underground aquifer. Since stabilized sludges generally have significantly different physical properties than untreated sludges, vegetation and landscaping can be promoted with minimal pollution problems. A recent study of public reaction to solid waste disposal practices (Ref. 172) reported that more than half of those citizens who object to landfill disposal would find it acceptable if the site were to be recalimed as a recreation area.

SECTION IX

SELECTION OF CHEMICAL AND PHYSICAL REGULATING PARAMETERS

RATIONALE FOR CHEMICAL REGULATING PARAMETERS

Various rationale are available for establishing chemical regulating parameters for FGC sludge disposal. Under normal disposal conditions, the important environmental considerations related to chemical characteristics are groundwater and surface water protection. Hence, the chemical regulating parameters of interest would be those associated with the liquid phases of the sludge rather than the solid phases.

The chemical regulating parameters selected should satisfy the following criteria:

- Accurate correlation with environmental impacts

- Usefulness as an indicator of the migration of many contaminants aside from itself

- Simplicity of measurement

- High measurement accuracy and reproducibility

- Low analytical cost

Section VIII discussed the chemical parameters of major concern when assessing FGC sludge environmental impact. The following chemical parameters could possibly have adverse environmental impacts at the disposal site:

- Total dissolved solids (TDS)
- Boron
- Fluoride
- Mercury
- Lead
- Selenium

If large volumes of sludge accidently enter a water course, the COD concentration will also be important.

Generally, the regulating agency will not be concerned with the chemical contaminant concentrations of the FGD sludge liquid phase itself, but rather will concern itself with the rate of escape of these contaminants from the disposal site into the surrounding environment. As discussed in Appendix A, differing rates of chemical contaminant escape will be acceptable for different sites, depending upon the specific site conditions. The problem then is selection of the chemical parameters which are best for measuring the rate of escape of chemical contaminants from the site.

Groundwater monitoring programs should be designed to warn of contamination by a disposal site in time for corrective action to be taken. Both concentrations of contaminants in leachate and the rate of leachate migration are important. The rate of contaminant movement through a soil varies according to soil composition and other site conditions. Of the chemical parameters which are useful indicators of leachate migration, TDS concentration is the simplest to measure. Sodium and calcium salts are the major components of TDS in FGC sludge liquors. Under normal soil conditions, cation exchange sites on soil particles are occupied by sodium and calcium ions. This would preclude ion exchange reactions with sludge leachate TDS, allowing the TDS profile to penetrate the soil faster than most other measurable parameters.

In view of these considerations, the TDS concentration is the best chemical regulating parameter for groundwater monitoring of FGD sludge disposal sites. A review of Section VI "Waste Characterization" shows that the relationship between the liquid phase TDS concentration and the concentrations of the other chemical contaminants of concern are as shown in Table 37. By regulating the TDS contaminant escape, control of all the other contaminant of concern is also achieved.

It would, of course, be necessary to periodically measure the liquid phase concentrations of all the contaminants of possible concern listed in Table 37 to verify that the ratios between TDS and each contaminant were remaining sufficiently high to ensure that TDS was a reliable "indicator." Such periodic liquid phase analysis would warn of unusual situations where the ratio of TDS to concentration of other contaminants was lowered by dilution, and limits upon TDS mass transport from the site might require appropriate modification.

RATIONALE FOR PHYSICAL REGULATING PARAMETERS

The physical properties of FGC sludges are important to the following disposal site considerations:

- Future land use
- Rate of mass transport of contaminants from the site

TABLE 37. CHEMICAL CONTAMINANT RELATIONSHIPS IN FGC SLUDGE LIQUID PHASE.

Contaminant	Typical Concentration Range, mg/l		Ratio of TDS to Contaminant		Drinking Water Standards TDS/Contaminant*
	Low	High	Low	High	
Total Dissolved Solids (TDS)	2500	95000	1:1	1:1	1:1
Boron (B)	8	41	300:1	2300:1	250:1**
Fluoride (F)	0.7	70	3600:1	1300:1	500:1
Mercury (Hg)	.001	.07	2.5M:1	135K:1	250K:1
Lead (Pb)	.001	.55	2.5M:1	172K:1	10K:1
Selenium (Se)	.001	2.7	2.5M:1	35K:1	10K:1

* Federal Register, p. 59570, December 24, 1975, assume 500mg/l TDS standard.

** Assumed Limit of 2.0mg/l Boron (Irrigation Water Quality).

$M = 10^6$

$K = 10^3$

- Sludge flow during accidental catastropic release.

The relevant physical properties for untreated and stabilized sludges were discussed in Sections VI and VII, respectively.

Load bearing strength is the physical property most often associated with land use restrictions. In areas where construction is anticipated, a structurally stable sludge is often necessary. However, engineers can design foundations to compensate for variations in site characteristics. Buildings have been built on soft clays, thixotropic clays, sanitary landfills, and other equally poor structural conditions.

Load bearing strength of the closed disposal site should be, at a minimum,sufficient to support recreational uses. Once these minimum criteria are met, light construction would probably present little problem on a closed and reclaimed pond or landfill of normal depth (5 to 20 meters). Actually load bearing strength is often correlated with high compression and the low permeability often accompanying it. This could create problems in residential developments when trying to cultivate lawns, shrubs, and trees. Load bearing strength should therefore be used as a regulating parameter only in tandem with the specific proposed use of the reclaimed site and the desired permeability for groundwater protection.

For agricultural use, the reclaimed disposal site should have the following physical characteristics:

- Good site drainage;
- High rain water input through the sludge surface to flush out the soluble salts;
- Little or no sulfite content or COD;
- Soft structure with high void volume.

If the sludge is first stabilized before disposal, the feasibility of using the site for agricultural purposes is actually reduced. Most commercially available processes reduce the sludge permeability and increase the pH, both of which decrease the availability of plant nutrients such as phosphorus, iron, and zinc. Even covering the site with top soil may not work without adequate planning for drainage of the added soil. Conversely, the chemical properties of raw sludge would also make the reclaimed site unsuitable for agricultural use (TDS, pH, and boron contents).

Establishing a physical regulatory parameter for FGD sludge disposal in agricultural areas is therefore of little value due to this dichotomy.

One physical characteristic of certain FGD sludges which can strongly affect the range of potential site reclamation schemes is their thixotropic nature. This property allows the sludge to change state from a solid to a liquid upon heating, vibration, or other loadings without a change in moisture content. This phenomenon depends upon the specific sludge and its moisture content. It is a hazard to buildings and other objects on the site unless accounted for through stabilization or proper foundation design.

Thixotropic sludges are also a potential hazard during impoundment failure. The vibration accompanying the catastrophic release of supernatant may be sufficient to liquify the settled material. Sulfite sludges in particular exhibit this behavior; these sludges also exert high COD, therefore compounding the problem. With non-thixotropic sludges, the amount of solids which would exit through a dike break would be much smaller. Resuspension of settled solids would be minimal in comparison to the liquification of the solid mass.

The physical properties of FGD sludge which affect the mass transport of contaminants are sludge permeability and hydraulic head. For a given hydraulic head, the lowest permeability between the sludge and the underlying soil will determine the rate of leachate movement. Similarly, a large hydraulic head will drive leachate through even low permeability sludge. These two physical parameters should certainly be employed as evaluation criteria, but the overall rate of mass transport from the disposal site is the real regulating parameter. It is a function of both physical and chemical parameters of the sludge and the site. The rate of mass transport is determined using a chemical regulating parameter.

Based on the above discussion, it appears that no one physical parameter can be used to regulate FGD sludge disposal in an absolute fashion. As load bearing strength and thixotropy are the most important physical characteristics to a disposal operation, the best physical regulating parameter is stability as it relates to load bearing strength. Stability is a qualitative measure of a materials load supporting properties, based both upon present strength and changes in physical properties with time.

Stability as it is used here is a relative measure. There is no absolute division between stable and unstable sludge for all applications, only for each individual disposal situation. Stability can therefore be redefined as necessary for each application.

Evaluation criteria for stability should be specific to each site, with the principle criteria being (1) the eventual use of the land, and (2) the expected time before that use will begin. For example, an urban sludge disposal site should be stable immediately upon closure so that reclamation and use can begin, with the degree of stability being dependent upon the expected land use. A rural, non-agricultural site on the other hand might not require immediate stability. Land use projections would be needed, as well as some estimate of the stabilization rate (e.g., natural dewatering, oxidation, compaction, etc.). In other words, the physical properties of FGD sludge should be regulated based on when the disposal site will support a reuse function at some time in the future. That time and that function are site specific.

It appears that research is required to place quantitative values upon the in-place stability over time of FGD sludge of various compositions, both untreated and treated. Research to date has not provided a sufficient data base for assessing in-place stability for FGD sludge of a specific composition.

SECTION X

THE COST OF FGD SLUDGE DISPOSAL

INTRODUCTION

The cost information presented in this section is based upon data derived from other reports - data that were fragmented and, in some instances, based upon minimal actual operating or engineering cost information. This is understandable, since none of the completed studies had cost analysis as a primary objective. Several newer, as yet uncompleted studies, however, are focusing on the development of comprehensive cost analyses; these studies will become available during 1977 and 1978.

In light of the constraints imposed by limited data, this section should be viewed as a digest of preliminary cost information available in late 1976, not as a definitive cost analysis of FGD disposal alternatives.

A utility faced with control of an SO_x emissions problem has to make economic decisions in the following broad areas, many of which are interrelated:

- Whether to convert to a low sulfur fuel, entirely eliminating the need for an FGD system;
- If it is decided to install an FGD system that produces throwaway sludge, the kind of scrubber units to use (which, of course, affects the volume and character of the raw FGD sludge generated);
- Pretreatment of the raw FGD sludge, e.g., dewatering and filtration (which again affects the volume and character of the FGD sludge to be disposed);
- Mode of FGD sludge transport;
- Stabilization of the FGD sludge by noncommercial or commercial processes;
- Method of final disposal.

This section provides cost information for the last two economic decision areas, i.e., stabilization and final disposal.

Reliable cost information in the other areas is not yet available.

PUBLISHED COST ANALYSES OF FGD SLUDGE DISPOSAL

Costs of lime/limestone throwaway sludge disposal have been included in the following reports:

- Solid Waste Disposal (Radian Corp., Ref. 135)
- Disposal of By-Products from Non-Regenerable Flue Gas Desulfurization Systems: Initial Report (Aerospace Corp., Ref. 139)
- Disposal of Flue Gas Cleaning Wastes: EPA Shawnee Field Evaluation, Initial Report (Aerospace Corp., Ref. 47)
- Sulfur Oxide Throwaway Sludge Evaluation Panel (SOTSEP), Technical Discussion (Princiotta, NERC/EPA, Ref. 129).

These reports, due to their general nature, could not include many site-specific variables in their analyses. The assumptions made were necessarily broad in nature, and the only sludge disposal alternatives considered were the following:

- Stabilization using commercial systems offered by I U Conversion Systems, Inc., Dravo Corp., and Chemfix Corp. (Carborendum). Although these are not the only commercially available processes, they received the most attention in 1972-1976 EPA research.
- Final disposal into lined ponds. Cost estimates for unlined pond construction, although not provided by the reports, were derived from the data presented, for use in this analysis.

A review of the existing cost literature on FGD sludge disposal revealed that each study defined a model plant upon which to base estimates. Variations of interest between plants included the coal characteristics (percent sulfur and ash), the power plant size and load factor, and sludge generation rate based upon these other parameters. Table 38 lists the important model plant parameters given by each study. These parameters were used to derive FGD sludge disposal cost figures which could be compared between studies.

Comparison of Cost Estimates

Table 39 summarizes the results of the cost data survey. The table begins with the date of report and sludge generation estimate per MWh from each data source. This information is followed by an estimate of disposal costs per ton of dry sludge

TABLE 38. MODEL PLANT PARAMETERS GIVEN IN RECENT FGD SLUDGE DISPOSAL COST STUDIES

Parameter*	Radian (Ref. 135) May 1974	Aerospace (Ref. 139) May 1974	Aerospace (Ref. 141) Aug. 1974	Aerospace (Ref. 47) July 1975	SOTSEP (Ref. 126) Apr. 1975
Date of Report	5/74	5/74	8/74	7/75	4/75
% Sulfur of Coal	3	3	3		3.5
% Ash of Coal	12	12	12		12
Plant Capacity in MW	1000	1000	1000	1000	1000
Hours of Operation/Year	6400	6400	4560	4380	6400
Million Tons Coal/Year					
Tons Coal/MWh	.4			.40	.40
Tons Dry Sludge/Ton Coal				.28	
Million Tons Dry Sludge/Year	.71	.65	.46		.69
Tons Dry Sludge/MWh					

*All tons are metric

TABLE 39. SUMMARY OF FGD SLUDGE DISPOSAL SYSTEMS COST DATA BASE

Disposal Technique		Radian (Ref. 135) May 1974	Aerospace (Ref. 139) May 1974	Aerospace (Ref. 141) Aug. 1974	Aerospace (Ref. 47) July 1975	SOTSEP (Ref. 129) Apr. 1975
	Tons dry sludge/MWh*	.111	.102	.102	.113	.108
Lined Ponding	$ per Ton Dry Sludge	--	4.42-14.24	5.00-9.00	--	5.00-9.00
	mills/kWh	--	.45-1.43	.51-.92	--	.54-.97
IUCS** Stabilization	$ per Ton Dry Sludge	1.65-2.76	3.30-5.52	8.00-10.00	7.20-9.20	8.00-10.00
	mills/kWh	.18-.31	.32-.54	.82-1.02	.82-1.04	.86-1.08
Dravo Stabilization	$ per Ton Dry Sludge	2.75-8.25	3.30-6.62	4.00-12.00	5.80-8.80	7.40-10.00
	mills/kWh	.30-.91	.32-.67	.41-1.22	.66-1.00	.80-1.08
Chemfix Stabilization	$ per Ton Dry Sludge	11.00	11.02	8.00-10.00	8.50-11.50	8.00-10.00
	mills/kWh	1.20	1.12	.82-1.02	.97-1.30	.86-1.08

*All tons are metric
**Includes fly ash disposal

and disposal costs in mills per kWh for each of the five alternate means of disposal. It should be noted that estimates of generated tons of dry sludge are similar in all studies. Moreover, the technique of presenting data from each study and for each disposal alternative in terms of disposal cost per ton dry sludge and disposal cost/kWh allows (1) comparisons between references for a particular disposal alternative and (2) comparisons between alternatives for a given study. On the basis of such comparisons, it appears that cost estimates for the various disposal options may be increasing over time and are also developing more narrowly defined ranges. These trends are consonant with general cost inflation and with developing understanding of technology requirements for disposal implementation.

Appendix A of this report discusses conditions under which unlined ponding may be environmentally acceptable; it is a fact that most FGD sludge is disposed into unlined ponds. Cost estimates for this disposal alternative were not explicitly developed by the three studies that discussed artificially lined ponds. However, Table 40 presents a method for obtaining unlined ponding estimates from the liner cost information provided by these studies. The first six items in Table 40 are merely restated from Table 39 or from the preceding discussion of each data source.

The estimated liner costs in terms of dollars per ton dry sludge and mills per kWh are derived from the preceding items in the table. That is, the liner cost per ton dry sludge is the product of liner cost per ton processed and tons processed per ton dry sludge. Similarly, mills of disposal costs per kWh is the product of the liner cost per ton dry sludge and tons of dry sludge per MWh. The last two items in Table 40 were derived by subtracting the appropriate estimates of liner costs from the published estimates of lined ponding disposal costs.

With these estimated disposal costs for unlined ponding, it is now possible to summarize, in Table 41, the available cost information for the state-of-the-art in FGD sludge disposal alternatives. The table does not include cost estimates for such disposal alternatives as mine or ocean; the feasibility of such alternatives is highly site-specific. The costs of ocean and mine disposal are currently being developed by A. D. Little, Inc., as part of the EPA FGD Waste and Water Program, and the State University of New York.

In Table 41, it appears that unlined ponding is approximately \$3 to \$10 less expensive per ton of dry sludge and approximately .3 to 1.0 mills less expensive/kWh than lined ponding. Moreover, Table 41 appears to show that both unlined and lined ponding is less expensive than commercial stabilization for power stations that have a choice under current

TABLE 40. COMPUTATION OF UNLINED PONDING COSTS FROM AVAILABLE INFORMATION*

Disposal Item	Source Data	Aerospace (Ref. 139) May 1974	Aerospace (Ref. 141) Aug. 1974	SOTSEP (Ref. 129) April 1975
	Tons Dry Sludge/ MWh	.102	.102	.108
Lined Ponding	$/Ton Dry Sludge	4.42-14.24	5.00-9.00	5.00-9.00
	Mills/kWh	.45- 1.45	.51- .92	.54- .97
Estimates of Pond Liner Costs (Installed)	Tons Processed/ Ton Dry Sludge	2	2	2
	$/Ton Processed	1.38- 5.01	1.50-2.75	1.50-2.75
	$/Ton Dry Sludge	2.76-10.02	3.00-5.50	3.00-5.50
	Mills/kWh	.27- 1.02	.31- .56	.32- .59
Estimated Unlined Ponding Costs	$/Ton Dry Sludge	1.66- 4.22	2.00-3.50	2.00-3.50
	Mills/kWh	.17- .43	.20- .36	.22- .38

* All tons are metric

TABLE 41. SUMMARY OF FGD SLUDGE DISPOSAL SYSTEMS COST DATA BASE, INCLUDING UNLINED PONDING*

Disposal Technique	Disposal Costs	Radian (Ref. 135) May 1974	Aerospace (Ref. 139) May 1974	Aerospace (Ref. 141) Aug. 1974	Aerospace (Ref. 47) March 1976	SOTSEP (Ref. 129) April 1975
Unlined Ponding	$/Dry Ton Sludge	-	1.66- 4.22	2.00- 3.50	-	2.00- 3.50
	Mills/kWh	-	.17- .43	.20- .36	-	.22- .38
Lined Ponding	$/Dry Ton Sludge	-	4.42-14.24	5.00- 9.00	-	5.00- 9.00
	Mills/kWh	-	.45- 1.43	.51- .92	-	.54- .97
IUCS** Fixation	$/Dry Ton Sludge	1.65- 2.76	3.30- 5.52	8.00-10.00	7.20- 9.20	8.00-10.00
	Mills/kWh	.18- .31	.28- .46	.82- 1.02	.82- 1.04	.86- 1.08
Dravo Fixation	$/Dry Ton Sludge	2.75- 8.25	3.30- 6.62	4.00-12.00	5.80- 8.80	7.40-10.00
	Mills/kWh	.30- .91	.28- .55	.41- 1.22	.66- 1.00	.80-1.08
Chemfix Fixation	$/Dry Ton Sludge	11.00	11.02	8.00-10.00	8.50-11.50	8.00-10.00
	Mills/kWh	1.20	1.12	.82- 1.02	.97- 1.30	.86- 1.08

* All tons are metric

** Includes fly ash disposal

regulations. In addition, it appears that noticeable cost differentials also exist between the commercial stabilization processes.

Table 41 cannot be used to predict (except in very general terms) the actual cost ranking of alternatives that a given power station will experience. These cost estimates were developed for a hypothetical 1,000-MW power station; they provide only a slight indication of how changes in plant size or location would affect the hierarchical ranking of the alternative cost estimates. An option that appears to be relatively inexpensive for the hypothetical 1,000-MW plant might very well prove to be more expensive for a smaller system, when scaled down to the requirements of the smaller system. In addition to scale economies, many other site-specific variables, such as land costs of availability of input raw materials, will determine the disposal regimes actually available to a given utility. Stabilization processes such as IUCS which include fly ash disposal will show an economic credit for normal ash disposal operations.

FORTHCOMING COST ANALYSES OF FGC SLUDGE DISPOSAL

The preceding section summarized currently available cost information for FGC sludge commercial stabilization and pond disposal. Several more detailed economic studies are presently in progress. Two of these studies are:

- Conceptual Design and Cost Studies of Alternative Methods for Lime and Limestone Scrubbing Waste Disposal (Tennessee Valley Authority, Interagency Agreement No. D5-E-721)

- Environmental Effects and Control of Various Flue Gas Cleaning FGC Sludge Disposal Options (SCS Engineers, EPA Contract No. 68-03-2471)

TVA: Conceptual Design and Cost Analysis of FGC Sludge Disposal

In this study, the Tennessee Valley Authority, Muscle Shoals, Alabama, will use its extensive knowledge of the lime-limestone scrubbing process and a cost-oriented computer model to perform detailed economic evaluation of several FGC waste treatment and disposal options. Iterative runs of the computer model will use the following parameter variations:

- Power station size - 200, 500, and 1,500 MW;

- Power station age - new, 5, 10, and 15 years old, with 30 year life span;

- Coal sulfur - 2, 3.5, and 5 percent;

- Coal ash - 12, 16, and 20 percent;
- Fly ash removal, separate and combined with SO_2 scrubbing;
- Sludge solids prior to disposal - 15, 35, and 60 percent;
- Lined and unlined ponding;
- Commercial stabilization - Dravo, IUCS, and Chemfix processes; and
- Transport to disposal site - 1, 3, 5, and 10 mi.

The outputs of each scenario should provide a detailed analysis of the various direct and indirect disposal costs over each year of the remaining life of the power station and disposal site. Study results are expected in late 1977.

SCS Engineers: Economic Assessment of FGC Sludge Disposal

The primary objectives of this project are:

Phase I. To develop a better understanding of the thermodynamics and kinetics of chemical speciation in FGC sludge and sludge liquors.

Phase II. To assess the economic impact of various FGC sludge disposal regulatory approaches on the utility industry.

Phase II will involve the development of a detailed economic impact document for national FGD sludge disposal regulations. A family of cost curves will be developed relating disposal costs to the goals of the ultimate disposal operation (i.e., reduced permeability, increased load bearing strength). These costs will be exemplified by several model power plants and a subsequent analysis of regulatory impact on FGC sludge disposal operations.

Specifically, the following tasks are to be completed in this study:

- Compile and evaluate information on the available sludge disposal options and their associated regulatory approaches;
- Standardize current cost information into unit cost estimates for creation of typical sludge management systems;
- Use these typical systems to generate a preliminary assessment of the economic impact of regulatory compliance on the utility industry;

- Verify the analysis inputs with a committee of industry experts.

This study will utilize the information presented earlier in this section and data from other economic studies completed before mid-1978.

SECTION XI

APPLICABLE EXISTING STANDARDS/REGULATIONS

INTRODUCTION

The regulation of sludge disposal from flue gas desulfurization (FGD) operations has not been uniform to date. Pending the promulgation of specific guidance from federal regulatory agencies, state and local agencies have generally relied upon existing standards/regulations designed for the disposal of other forms of waste.

Regulations that have been or could be applied to FGD sludge disposal practices fall under one or more of the following classifications:

- Solid waste disposal
- Hazardous waste disposal
- Wastewater disposal
- Water quality criteria for various beneficial uses
- Comprehensive air quality criteria
- Waste disposal to oceans
- Waste disposal to mines

In implementing a sludge disposal plan, some FGD-equipped power plants have had to comply with one or more of the above regulations.

The major environmental problems potentially associated with FGD sludge disposal include:

- Groundwater and surface water contamination from leaching of trace metals and dissolved solids;

- Future beneficial use of the disposal areas;

- Failure of the sludge pond retaining structure and subsequent discharge to surface waters;

- Floods or other extraordinary conditions that might cause the sludge to enter the biosphere.

These potential problems may fall under several jurisdictions in some states and go unregulated in other states. The purpose of this chapter is to summarize the applicability of existing and/or proposed standards/regulations to the sludge disposal techniques currently available. The applicability criteria will in most cases regard the four potential environmental problems listed above.

SOLID WASTE DISPOSAL

The predominant methods of solid waste disposal in the U.S. are landfill and incineration. Other techniques account for only a small percentage of the waste. Regulations governing the disposal of solid wastes typically apply to specific waste classifications such as municipal refuse, brush and tree wastes, demolition and construction debris, sewage sludge, and bulky wastes such as abandoned automobiles and appliances. Other solid waste categories, specifically certain industrial sludges, are sometimes mentioned as being similar to FGD sludge. These categories are discussed in the subsection of this section entitled "Hazardous Waste Disposal."

Of the four potential environmental concerns associated with FGD sludge disposal, all but dike failure are used to evaluate land disposal practices for solid waste. The percolation of water through landfills has been shown to leach various organic and inorganic contaminants from solid waste with the potential of polluting ground and surface waters. Landfill sites are generally situated outside of flood plains to avoid flooding and severe erosion of the waste and cover material. Site reclamation, although once considered unsafe, is now a common practice; many recent landfill designs have predestined sites for use as parks, golf courses, etc.

Regulatory agencies usually require that leachate and flooding dangers be accounted for and that reclamation plans be specified in the landfill design. The following is a summary of federal and state solid waste disposal criteria as they may apply to FGD sludges.

Federal Solid Waste Regulations

In the past, regulation of solid waste disposal activities in the U.S. has fallen under the jurisdiction of state and local agencies. Until October 1976, federal agencies served only to provide guidelines and technical assistance for solid waste disposal, under authority of the Solid Waste Act of 1965. On October 21, 1976, the Resource Conservation and Recovery Act of 1976 was signed into law. This act, built on the Solid Waste Disposal Act of 1965 and the Resource Recovery Act of 1970, by statute establishes the Office of Solid Waste within EPA to guide the implementation of the law, and establishes a federal/state/local government partnership to share the implementation.

The regulations which will be promulgated in April 1978 will define hazardous wastes and set forth a management control system for these wastes. The effect of these regulations on the generation and disposal of FGC wastes is as yet uncertain. Should any portion of these wastes be defined as hazardous wastes by either EPA or any of the states, a state permit system would then be effected according to generation, transportation, storage, and disposal criteria.

The U.S. EPA has formulated general guidelines and recommended procedures for the land disposal of municipal solid waste (Federal Register, 39(158):29327-37). Included under "Requirements and Recommended Procedures (Subpart B)" are evaluation criteria for potential groundwater contamination, flooding, and site reclamation.

Recommended design considerations to protect water quality at a land disposal site include specification of:

- Groundwater elevation and movement
- Initial quality of surrounding water resources
- Soil and geological conditions
- Potential for leachate generation
- Location of monitoring wells
- Testing procedure (24.204-2(a))

It is also suggested that leachate collection systems be provided where necessary and that compliance with water quality protection provisions be required.

With regard to flooding dangers, it is recommended that land disposal sites "be protected against at least the 50-year design flood by impervious dikes and other appropriate means" (241.204-2(b)).

Site reclamation procedures should include a proper amount of cover material and vegetative growth. Final cover should be applied to completed areas or areas that will remain idle for over a year and should be at least 2 ft thick (241.209-3(c)). Vegetative growth should be promoted "as promptly as possible to . . . improve (the) appearance of idle and completed areas" (241.209-2(c)).

State Solid Waste Regulations

Examination of the solid waste regulations for each of the 50 states revealed some notation of groundwater protection, flood plain consideration, and site reclamation in almost every case. The degree of specificity varied significantly, however, as many states prefer a permit system and reserve the right to evaluate criteria on a site-specific basis.

Many of the power plants employing FGD were subject to disposal site approval by state solid waste agencies. Site evaluation was usually limited to a soils analysis, including permeability and chemical analysis. Contact with the state agencies revealed that FGD site evaluation criteria were generally excerpted from applicable landfill requirements, since specific FGD sludge disposal site evaluation criteria were not available. As an example, the Pennsylvania Department of Environmental Resources (PDER), Division of Solid Waste Management, accepted monitoring responsibility for the fixated sludge pond at the Duquesne Light Company's Phillips Station, yet they referred the associated untreated sludge lagoons to another division of PDER.

The following subsections specify detailed passages from selected state solid waste management regulations that could be excerpted to apply to FGD sludge disposal.

Leachate from Sludge Disposal--

Most states have adopted the federal recommendation for protecting groundwater quality beneath solid waste disposal sites without significant extrapolation. Some, however, have specified modified restrictions which might be pertinent to site design and location. Excerpts from nine such state regulations follow:

Iowa Solid Waste Title IV 27.1(5)(g). An acceptable landfill site is:

> 1. So situated as to obviate any significant, predictable lateral leakage of leachates from the landfill to shallow unconsolidated aquifers that are in actual use or are deemed to be of potential use as a water resource.
>
> 2. So situated that the base of the proposed landfill is at least five feet above the high water table unless a lesser separation is unlikely to have a significant effect on ground and surface waters.
>
> 3. Not in significant hydrologic subsurface or surface connection with standing or flowing surface water.
>
> 4. Not situated in an unconsolidated sequence that will permit more than 0.004 cubic foot of liquid per day per square foot of area downward leakage into a subcropping bedrock or alluvial aquifer if such an aquifer is present beneath or adjacent to the proposed site. . .
>
> 5. At least 1,000 feet from any well in existence at the time of application for the original permit. . .
>
> 6. At least one mile from a public water supply or well or a public water supply water intake from a body of

static water or one mile upstream or 1,000 feet downstream from a riverine intake.

Indiana (SPC 8, Chapter III, Section 6).

c. In no case shall solid waste be deposited within an aquifer. A barrier of undisturbed soil shall be maintained between the lowest portion of deposited refuse and the aquifer of a thickness to be determined by the Board based upon permeability and ion exchange properties.

Maine (Title 38, M.R.S.A. 1302 406.1 Site Approval).

a. The surficial material soils, underlying the refuse to a depth of at least 5 feet shall be well graded granular material containing from 15-40% fines, and being relatively free of cobbles in excess of 6 inches in diameter.

b. All refuse shall be placed at least 5 feet above groundwater.

c. The site should be moderately sloped, i.e., less than 15 percent.

d. The site boundary shall not lie closer to a classified body of water than 300 feet.

e. The site boundary shall not lie closer to the nearest residence or potable water supply than 1,000 feet.

Oregon (Oregon Administrative Rules, Chapter 340, Division 6, Subdivision 1).

4. Sewage Sludge Lagoon and Sludge Spreading Area Design. Construction, and Operation.

a. Location.

Sludge lagoons shall be located a minimum of 1/4 mile from the nearest residence other than that of the lagoon operator or attendant.

e. Type of Sludge Lagoon.

Lagoons shall be designed and constructed to be non-overflow and water tight.

h. Sludge Removal from Lagoon.

Water or sludge shall not be pumped or otherwise removed from a lagoon, except in accordance with a plan approved in writing by the Department.

i. Monitoring Wells.

> Lagoon sites . . . having . . . potential for contaminating usable groundwater resources may be required to provide groundwater monitoring wells . . . Said monitoring wells shall be sufficient to detect the movement of groundwater and easily capable of being pumped to obtain water samples.

Texas (Solid Waste Regulations, Section E, E-1.4 - Water Pollution).

> b. Solid waste shall not be placed in unconfined waters which are subject to free movement on the surface, in the ground, or within a larger body of water.
>
> c. Solid waste shall be deposited in such a manner that the possibility of leachate percolating into the groundwater is minimized. An impervious barrier may be either naturally occurring or artificially placed. The following procedures are acceptable:
>
> 1. Placement of three feet of clay.
>
> 2. Placement and compaction of one foot of selected clayey material under optimum moisture conditions.
>
> 3. Placement of an impervious membrane of asphaltic, plastic, or other approved material.
>
> f. If deemed necessary by the Department, monitor wells will be drilled . . . to observe changes in the quality of groundwater.

New Jersey (N.J.A.C. Rules 7:26-1 et seq. 7:26-2.6.4.3.).

> Any solid waste facility accepting . . . chemical wastes . . . shall install monitoring wells which are constructed and located in accordance with instructions available from the Department. Samples shall be taken from each well and analyzed by a laboratory acceptable to the Department at least once every three months . . . (also,) An acceptable system of interception, collection, and treatment shall be implemented . . . (as of) September 15, 1975.

Oklahoma (Disposal of Solid Waste, Regulation 5).

> 5.3 An impervious lining or membrane may be required by the Department for a site or facility for any given waste deposited therein. Plans and specifications for such a lining or membrane must be approved by the Department before installation or use.

> a. The use of natural or specific clays to develop any necessary lining is permitted providing: That the lining is at least 5 feet thick and that the permeability index is no greater than 10^{-8} cm/sec . . .

5.4.1 Soil Characteristics. The soil characteristics of the subject disposal site used for land disposal of hazardous wastes shall meet the following criteria:

> a. The soil shall meet the classification of a clay consisting of no more than seventy percent (70%) of particles larger than 0.002 millimeters. The soils shall be of inorganic nature and origin.
>
> b. The permeability of the clay soil shall be no greater than 10^{-6} cm/sec . . . Soil testing shall be performed . . . to a depth of at least ten (10) feet from the farthest reach of the disposal area in all directions.

Delaware (Chapter 1 - Disposal Regulation, Section 7, Industrial Landfill Standards).

7.01 . . . The chemical and physical properties of the industrial waste and its leachability characteristics in a neutral, acidic, and basic environment shall be documented. The design shall include plans for a leachate collection, treatment and disposal system.

7.03(g). All leachate shall be collected and treated so as to provide a degree of removal of pollutants reflecting the application of a practicable level of technology. The extent of the design of this collection and treatment system shall depend on the chemical and physical properties of the industrial waste and in particular its leachability characteristics. When deemed necessary by the Department, disposal areas and leachate collection ditches and ponds shall be lined with an impermeable liner. A synthetic impermeable liner shall be installed unless the applicant can prove to the satisfaction of the Department that a natural soil liner is impermeable . . . Wells or other monitoring devices shall be installed.

Nevada (Solid Waste Management Regulations, Article 2).

2.6.1.b. Hazardous liquid wastes shall be processed in such a manner so that the waste will be neutralized or solidified.

> c. A completed hazardous waste burial area shall be covered with a layer of suitable cover material compacted to a minimum uniform depth of thirty-six (36) inches.

It should be noted that most states which require groundwater monitoring during operation of the fill also require the monitoring to continue for a specified period after closure.

Flooding and Drainage Considerations--

Most of the state solid waste disposal regulations address the problem of flooding, and all regulations mention or specify the fill slope necessary to divert runoff water.

Flood consideration varies with each regulation, from simple mention of the potential danger to specifications regarding site location based on flood probability. The following are typical examples:

Montana (Administrative Code, Title 16).

> 6(c)(iii) . . . sites shall not be subject to flooding by surface water or have a high groundwater table and shall not be located within a 100-year floodplain.

Kentucky (401 KAR 2:010).

> Section 9. (1) No landfill shall be exposed to a once in five (5) year flood. Landfills exposed to a once in 100 year flood shall be protected. Where applicable, empirical data shall be used to determine the frequency of flood exposure. Where published data is not available, the frequency of flood exposure shall be established by the unit hydrograph technique.

Iowa (SW Title IV).

> 27.1(5)g. (5) Outside a floodplain or shoreland, unless proper engineering and sealing of the site will render it acceptable and prior approval of the Iowa Natural Resources Council and where necessary the U.S. Corps of Engineers is obtained.

Provisions to eliminate standing water from landfills would obviously apply only to fixated or dried sludge lagoons. Most landfills are designed to include a surface grade; several state requirements are examples:

Oklahoma (Disposal of Solid Waste, Regulation 5).

> 4.1.23 Drainage of Surface Water. The entire site, including the fill surface, shall be graded and/or provided with drainage facilities to minimize runoff into and onto the fill, prevent erosion of washing of the fill, drain off rainwater falling on the fill and prevent the collection of standing water. The final surface of the fill shall be

graded to a slope of at least one percent, but no surface slope shall be so steep as to cause erosion of the cover.

New Jersey (N.J.A.C. Rules 7:26-1 et seq.).

All lifts shall be graded so as to facilitate drainage therefrom. Side slopes and working face shall not exceed a vertical rise of one (1) foot for each horizontal distance of two (2) feet.

Delaware (Chapter 1 - Disposal Regulations).

6.03(g) . . . Operations shall be planned and conducted so rainwater is drained off the fill or disposal area at all times. Standing water shall not be allowed on the fill at any time. The completed fill shall have a minimum slope of 2% to facilitate surface drainage and a maximum slope that precludes erosion.

Missouri (Board of Health Regulations).

2.52 A7. Provisions for surface water runoff control to minimize infiltration and erosion of cover material. On-site drainage structures and channels should be designed for at least a 20-year rainfall frequency.

Provisions for Site Reclamation--

The extent to which a landfill site is reclaimed is up to the owner. Many states do, however, require a certain amount of landscaping and planting to prevent devaluation of nearby properties, excessive erosion, or standing water accumulation. Reclaimed site uses vary, but most landfills are developed into recreation areas. The erection of structures over the fill is generally not recommended due to structural instability and subsidence. Site reclamation requirements set forth by several states are enumerated below.

Oklahoma (Disposal of Solid Waste, Regulation 5).

4.1.24 Final Grading. The completed fill shall be graded to serve the purpose for which the fill is ultimately planned. The surface drainage shall be consistent with the surrounding area. The finished construction shall not in any way cause interference with proper drainage of adjacent land nor shall the finished fill concentrate runoff waters into adjacent areas. Seeding of finished portions of the fill with appropriate vegetation to promote stabilization of the cover shall be performed.

Hawaii (Environmental Laws and Regulations, Vol. II, Chapter 46).

Section 3B

> 9. A completed landfill or a major portion thereof shall be covered with at least two (2) feet of compacted earth material, compacted, graded with proper drainage to minimize soil erosion and sodded or planted immediately after the grading work has been completed.
>
> 10. Provisions shall be made to maintain the landfill site for at least one year after termination of operation to prevent health hazards or nuisances from occurring. Maintenance shall include, but not be limited to, repair of cracks or fissures, repair of areas where settling occurs and control of problems which result from leachate or odors. Compliance with these requirements shall be a basis for future recommendations by the Department on land use.

Colorado (Regulations, Solid Waste Disposal Sites and Facilities).

> Section 4 j. Final Closure. Prior to closing a solid waste disposal site except for cause as set forth in Section 36-23-13 CRS as amended, the final cover of the deposited solid wastes shall be graded to the elevations which shall be shown in the initial design. The cover shall be of such thickness and material as will prevent the entrance or emergence of insects, rodents, or odors. Such closure elevations shall be such as will provide for the diversion of rainfall and runoff away from the fill area.

Illinois (IPCB Rules and Regulations, Chapter 7).

> Rule 318: Completion or Closure Requirements.
> a. The owner or operator of a sanitary landfill site shall monitor gas, water and settling at the completed site for a period of three years after the site is completed or closed.
>
> b. The owner or operator shall take whatever remedial action is necessary to abate any gas, water or settling problems which appear during the three year period.

Summary of Solid Waste Disposal Regulations--

As groundwater contamination, flood control, and site reclamation are all problems associated with FGD sludge disposal, it is apparent from the preceding excerpts that many states account for these same problems in their solid waste disposal regulations. In order to demonstrate the applicability of these regulations to sludge disposal operations, Table 42 summarizes the groundwater, flood protection, and site reclamation regulations for each state in which an FGD-equipped utility is presently located. These regulations do not necessarily represent the requirements that were applied to the FGD systems themselves, but serve only as an interpretation of the written

TABLE 42. STATE SOLID WASTE REGULATIONS PERTAINING TO SELECTED FGD SYSTEMS

State	Groundwater	Floods	Rainfall	Reclamation
AZ	General protection	None	None	2 ft minimum cover
CO	General protection	General rainfall protection	General rainfall protection	
FL	Monitoring, possible leachate collection	Away from flood plain	General diversion	2 ft minimum cover, 33% slope (sides)
IL	Monitoring, soil analysis	General rainfall protection	General rainfall protection	2 ft minimum cover, 50% slope (sides)
KS	General protection, soil analysis	None	None	State approval
KY	General protection, soil analysis	100 yr flood	General diversion	2 ft minimum cover, revegetation
MO	Monitoring, soil analysis, possible leachate collection	100 yr flood	20 yr rainfall	2 ft minimum cover, 33% slope (sides) revegetation
MT	General protection, soil analysis	100 yr flood	20 yr rainfall	2 ft minimum cover,
NV	Stabilize or neutralize	None	None	2 ft minimum cover, 2-4 slope
PA	Monitoring, soil analysis, possible leachate collection	50 yr away from flood plain	General diversion	2 ft minimum cover, 1-15% slope

regulations. Those state regulations that do not specifically refer to the given problem are indicated by the word "none."

HAZARDOUS WASTE DISPOSAL

Federal regulations controlling the disposal of certain industrial wastes could be applied to some extent to the disposal of FGD sludges. Similarities between these industrial wastes and FGD sludges are based on one or more common potentially hazardous constituents and/or a similarity in disposal methods.

The industrial wastes covered in this subsection are:

- Slimes from phosphate mining,
- Acid mine drainage,
- Gypsum from phosphoric acid manufacture,
- Coal mine tailings, and
- Coal ash disposal.

Although the emphasis here is on the various waste disposal regulations, a brief description of each individual waste is also presented.*

Phosphate Slimes

The mining and beneficiation of phosphate rock in the U.S. produces an estimated 38 million tons of waste slimes annually. About 75 percent of the country's phosphate mining is done in Florida and the remainder in North Carolina, Tennessee, and several western states.

Phosphate ore is mined primarily by the open pit method, although some underground mining is done in the West. Ore beneficiation involves a series of size reduction, washing, desliming, and flotation operations.

While raw phosphate slimes account for approximately one-third of the mined matrix, the various slurrying operations may produce waste slimes that occupy more than 150 percent of the original volume of mined material. Table 43 presents a range of chemical compositions for typical phosphate slimes solids.

Slime Disposal--

Phosphate slimes have traditionally been disposed of in decommissioned pit areas. Because of the volume increase from beneficiation, the pit capacity is necessarily increased by construction of earthen dams to form large settling ponds. The slime slurry is usually 4 to 6 percent solids when discharged to

---

*Unless otherwise noted, the supplementary information is excerpted from Ref. 135.

TABLE 43.* CHEMICAL COMPOSITION OF PHOSPHATE SLIMES SOLIDS

Chemical	Typical Analyses, Percent	Range, Percent
P_2O_5	9.06	9 - 17
SiO_2	45.68	31 - 46
Fe_2O_3	3.98	3 - 7
Al_2O_3	8.51	6 - 18
CaO	14.00	14 - 23
MgO	1.13	1 - 2
CO_2	0.80	0 - 1
F	0.87	0 - 1
LOI (1,000°C) †	10.60	9 - 16
BPL#	19.88	19 - 37

* Ref. 135

† LOI - Loss on Ignition

# BPL - Bone Phosphate of Lime

the settling pond. The colloidal nature of the solids makes dewatering difficult, and the maximum attainable solids content is 25 to 35 percent by gravity settling.

Research is under way to improve the dewatering potential of phosphate slimes for increasing supernatant recycle, to reduce settling pond area required, and to investigate possible slime beneficiation. Investigation of mechanical dewatering techniques has proved fruitless, due to high cost and limited effectiveness (50 percent solids maximum) of the techniques. Current emphasis is on improving the settling operation through the use of sand tailings, either as a drainage base or by controlled mixing with slimes in the settling basin. Preliminary indications are that improved dewatering, up to 80 percent solids content, is attainable. Details of the various methods under study can be found in the 1975 Annual Report for the Florida Phosphatic Clays Research Project.

Regulation of Slime Disposal--

A limited amount of research has been done to determine the extent of the various potential environmental hazards associated with phosphate slime disposal. Areas of interest thus far have been supernatant discharge, catastrophic dike failure, and pond seepage.

There appears to be no evidence of harmful effects upon aquatic life from slime pond supernatant release to nearby waterways, except for possible eutrophication due to the high phosphorus content of the liquor. In studies performed before pond liquor discharge was outlawed in Florida, no effect was noted on aquatic life except for an increase in algae growth in certain estuaries. No change in BOD was noted, although turbidity increased slightly.

Seepage resulting in groundwater contamination has not received attention as a problem area. Most phosphate mining companies monitor the streams below their plants on a daily basis, measuring water flow, suspended solids, phosphate, and fluorine; however, information on groundwater monitoring was not found in the literature.

The most critical potential slime disposal problem is catastrophic failure of the impoundment dams. Several instances of dam failure have occurred in Florida in the last 30 years; the most recent in 1971 released 2 billion gal of phosphate slime into the Peace River. All forms of marine life were killed for 60 miles of the river and in Charlotte Harbor (Ref. 117).

There are currently no federal regulations governing the disposal of slimes from phosphate mining operations. The state of Florida, however, has enacted "Minimum Requirements for

Earthen Dams, Phosphate, Mining and Processing Operations," for the purpose of preventing failures of earthen dams. Although existing requirements are specific to phosphate slime pond construction and maintenance, they could also apply to the ponding of FGD sludges due to the similar high COD concentration and volumes. Table 44 lists several relevant excerpts from the Florida requirements.

Acid Mine Drainage Sludge

The mining of coal and certain other ores exposes the pyrite (FeS_2) fraction to air and water, resulting in the formation of dilute sulfuric acid (pH 2-3) and suspended and dissolved iron sulfates.

Acid mine drainage (AMD) is normally treated to precipitate the iron and adjust the pH. It is subsequently ponded to allow for sedimentation, and the pond supernatant is drawn off and discharged to surface waters.

An estimated 8.2 million tons of AMD sludge (1-5 percent solids) are generated annually; Table 45 presents an analysis of a typical treated sludge.

Disposal of AMD Sludge--

AMD treatment takes place in four stages: pH adjustment, aeration, sedimentation, and disposal. The use of lagoons often consolidates the last two stages.

Neutralization reagents commonly used are lime, hydrated lime, and limestone; also used in some cases are sodium hydroxide and sodium carbonate. The reagent used influences the settling characteristics of the sludge. The carbonates yield a more granular, dense sludge with better dewatering characteristics than do hydroxides.

The purpose of aeration is to convert iron from the ferrous state to the ferric oxidation state, which precipitates more readily at low pH. Minimum solubilities for ferrous and ferric iron are achieved at pH 8.5-9.5 and 6-7, respectively. As the desired supernatant pH is 6-9, predominance of the ferric form reduces the quantity of reagent necessary.

As noted above, sedimentation characteristics of a sludge are primarily a function of the neutralizing reagent used. Research aimed at improving the normal settling rate and dewaterability of AMD sludge has considered both physical and chemical means. Table 46 summarizes reported research results. The most common method of final AMD sludge disposal is ponding.

TABLE 44. EXCERPTS FROM CHAPTER 17-9 OF THE FLORIDA RULES OF THE DEPARTMENT OF POLLUTION CONTROL

Section	Text	Relation to FGD Sludge Disposal
17-9.01	...There shall be no discharge from [phosphate slime] dams into the waters of the state of Florida...	Supernatant liquor discharge
17-9.03(1)(b)	A program of soil sampling and testing... shall be performed...including, but not limited to, the determination of in-place densities, shear strength, and permeabilities of the foundation and embankment soils...	Site characteristics
17-9.03(1)(e)	Minimum construction safety factors: 1.75 for horizontal shear at the base of fill, 1.5 for horizontal shear within the fill due to seepage within the outer face...	Pond construction
17-9.03(3)	Material...for dams shall be free of... extraneous matter which could affect the ...permeability or shear strength of the finished dam	Pond construction
17-9.03(5)(bi)	If dewatered to not less than 50% solids, the tailings may be deposited continuously (if impounded above natural ground level)	Pond operation
17-9.04(2)	The vegetative cover on retired dams shall be maintained sufficiently low to permit visual inspection of the soil surfaces...	Pond reclamation
17-9.05(3)(c)	...Inspection shall include...Determination of seepage characteristics through analysis of infrared aerial photographs or thermal imagery	Pond monitoring

TABLE 45.* AMD TREATMENT PROCESS AERATOR SLURRY ANALYSES

	Concentration
Slurry water	99.83
Filterable solids (percent)	.17
Solids analysis (percent):	
Fe	10.9
Ca	43.5
Mg	.4
Al	.6
Si	1.6
$SO_4^=$	14.4

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* Ref. 135

† The weight of aerator slurry retained on laboratory filter paper as a percent of the total slurry

TABLE 46.* RESULTS OF AMD SLUDGE DEWATERING RESEARCH

Technique	Percent Solids Achieved
Vacuum Filtration	
Lime treated	29.8
Limestone treated	45
Lime treated†	22
Limestone plus lime†	45
Limestone treated†	63
Pressure Filtration	
Batchwise	20-30
Semicontinuous	25
Freezing	7.5
Thickener/Clarifying	
Hydrated lime	.9-4.98
Limestone	12

* Ref. 135

† Using diatomaceous earth as a filter precoat

Disposal Regulations--

Regulations pertaining to the disposal of AMD sludges have been enacted on both the state and federal level. These regulations deal with the chemical character of the sludge and the design and maintenance of the impoundment structures. Potential applicability to FGD sludge disposal is found in the total suspended solids (TSS) and pH effluent limitations, and pond design guidelines.

A summary of existing effluent limitations for AMD liquors is presented in Table 47. Effluent limitations for TSS, iron, and pH have been implemented in Pennsylvania and West Virginia due to the predominance of deep mining. Federal regulations have also been applied to a variety of mining industries, coal mining is presently subject only to pH limitations.

Guidelines have also been established by the Mine Enforcement Safety Administration (MESA), Department of the Interior, for the design, construction, and maintenance of impounding structures for mining wastes. These guidelines can be applied to AMD sludge. The federal regulations derived from the MESA guidelines are similar to the phosphate slime storage guidelines presented in Table 44. The regulations emphasize the control of surface runoff, and maintenance and reclamation of the impounding structure.

No information on groundwater contamination from the lagooning of AMD sludges was found in the literature.

Gypsum from Phosphoric Acid Manufacture

The production of phosphoric acid - an intermediary in phosphate fertilizer manufacture - generates large volumes of gypsum as a by-product. Although gypsum is a valuable commodity in many countries, the abundance of higher quality gypsum in the U.S. generally precludes the marketing of the phosphogypsum, and most manufacturers dispose of it in diked ponds.

Phosphogypsum produced in the U.S. consists primarily of calcium sulfate dihydrate. The exact composition is dependent both on the particular rock source of phosphorus and the manufacturing process itself. Table 48 presents a chemical analysis of five gypsums from different ores.

Approximately 25 million tons of phosphogypsum were produced in 1969. The manufacturing process involves a reaction of the calcium phosphate mineral (usually fluoropatite, $Ca_3\ (PO_4)_2 \cdot CaF_2$) with sulfuric acid, precipitating hydrated calcium sulfate and forming phosphoric acid. The precipitate forms in needle-like rhombic crystals, whose character is determined by such variables as sulfate concentration, acid concentration, impurities in the rock, and slurry concentrations (Ref. 135).

TABLE 47. EFFLUENT LIMITATIONS FOR TREATED ACID MINE DRAINAGE

Jurisdiction (waste source)	Effluent Limitations (One-Day Maximum, mg/ℓ)				
			Iron		
	pH	Total Suspended Solids	Total	Dissolved	Suspended
Federal[†] (coal mining)	6.0-9.0	30[*]	4.0[*]	--	--
Federal[#] (iron ore mining)	6.0-9.0	30	--	--	2.0
Pennsylvania[**] (coal mining)	6.0-9.0	200	--	7.0	--
West Virginia[††] (coal mining)	5.0-5.9	--	10	--	--

[*] Proposed, Ref. 135

[†] EPA Effluent Guidelines and Standards for Ore Mining and Dressing, 40 CFR 440.12(a)(1)

[#] EPA Effluent Guidelines and Standards for Coal Mining, 40 CFR 434.32(a)

[**] Environmental Reporter, p 891:0743, 97.32 (1-5)

[††] Ref. 135

TABLE 48.* COMPOSITION OF TYPICAL BY-PRODUCT CALCIUM SULFATES FROM DIFFERENT ROCK SOURCES†

Rock Source	S	CaO	SiO_2	Al_2O_3	Fe_2O_3	P_2O_5	F
Florida	16.9	40.2	11.8	0.4#	--	0.9	--
Tennessee	20.6	39.4	7.5	0.6	0.4	1.9	0.4
Morocco	22.4	40.9	--	--	--	1.5	1.3
Morocco	17.1	30.2	1.2	1.7	0.7	--	--
Kola Peninsula	18.0	30.9	0.7	0.5	0.3	--	--

* Ref. 135

† Chemical analysis by weight percent

# Total Al_2O_3 and Fe_2O_3

Phosphogypsum Disposal--

Phosphogypsum is usually disposed of in diked ponds. The precipitate is filtered to a cake containing 18 to 35 percent water, and then either reslurried for piping or conveyed dry to the disposal area.

Pond design is presently governed by guidelines set forth by the Florida Phosphate Council. Most ponds are divided into sections, each operated individually. The drained gypsum is then either left to dry further or else is piled. The latter practice, designed to conserve space, has resulted in gypsum piles as large as 30 m high and 1.6 km long.

Phosphogypsum utilization has been limited by its impurities, particularly phosphates. However, possible uses are in the production of gypsum wallboard, gypsum plaster, plaster of Paris, cement, building blocks, and ammonium sulfate fertilizer.

Regulation of Phosphogypsum Disposal--

The environmental problems associated with gypsum disposal relate to (1) the ultimate disposition of the drainage water and supernatant liquor, and (2) the construction of the impoundment structures. The wastewater is either treated for discharge or is recycled to the plant. Dike construction, as noted earlier, follows guidelines established by the Florida Phosphate Council.

Federal regulations pertaining to phosphoric acid manufacture (40 CFR 422.22(a)) state that:

> "There shall be no discharge of process wastewater pollutants to navigable waters from the manufacture of phosphoric acid. . ."

However, it is assumed that the lime-clarification treatment process reduces pollutants to an effluent whose quality exceeds that of the receiving stream; the effluent can therefore be discharged.

Average annual treated pond discharges total between 2000 and 4000 ℓ/t of phosphate. Periods of heavy rainfall may cause discharges of up to 300 ℓ/sec for short intervals. While acid manufacturing regulations do not provide for rainfall compensation, federal gypsum processing regulations (40 CFR 436) do allow discharge of

> "that volume of water resulting from precipitation that exceeds the maximum safe surge capacity of a process wastewater impoundment . . . after application of the best practicable control technology currently available. . ."

This would appear to be applicable to both phosphogypsum and those FGD throwaway sludges that are high in calcium sulfate.

Gypsum pile runoff is generally captured in a series of drainage sluices and treated in a manner similar to pond discharge. Many acid manufacturers monitor waterways downstream of the ponds.

Data concerning groundwater contamination from pond or runoff leachate are unavailable.

Coal Mine Tailings

Coal mining and preparation operations generate large volumes of by-products, including uncovered coal, ash, slate, shales, and clay associated with the coal seam. Strip mining, in addition, generates huge amounts of waste cover material in the form of ugly spoil banks.

Coal preparation is accomplished in a series of steps, including crushing, sizing, impurities removal, and washing. Coarse coal is generally recovered using dense media separation, while fine coal is cleaned using a flotation process and a special floating agent. Coarse coal wastes are accumulated in so-called culm piles (also referred to as gab piles, coal refuse banks, or breaker refuse). The fine wastes (>1 mm) are usually discharged to a settling pond.

The composition of the coal wastes is dependent on the source of the coal and the cleaning efficiency. A selected coal waste characterization is shown in Table 49. The composition largely results from the engineering properties of the waste piles and from the extent of associated environmental hazards. Extensive sampling of both chemical composition and physical properties have been undertaken in recent years by the U.S. Bureau of Mines; their results are available in the literature (Ref. 157).

Disposal of Coal Mine Tailings--

The choice of a disposal method is site specific and includes consideration of site characteristics, transportation distance, disposal method alternatives, and site reclamation.

Since the enactment of reclamation regulations, site selection has depended primarily on ease of reclamation. Valley filling is one disposal method, as terracing is simplified. Backfilling of strip mines is also practiced, using the spoil banks as cover material in place of compacting and terracing. The use of flat disposal sites presents difficulty in both reclamation and environmental control. Most coal companies, however, continue to use existing waste piles, landscaping only the edges of the piles.

TABLE 49.* CHEMICAL AND PHYSICAL CHARACTERIZATION OF SELECTED COAL PREPARATION PLANT WASTES

Sample Description	Culm Bank (Gob) Material	Coal Fines[†]
Moisture (percent)	0.6	0.9
Ash (percent)	62.6	15.4
Sulfur (percent)	3.17	1.56
Carbon (percent)	23.32	78.31
Volatile matter (percent)	15.5	25.2
Loss on ignition	37.2	83.8
Btu	4,710	12,320
	Physical Properties	
Water solubility (percent)	1.4	.88
Water absorption (percent)	2.7	28.4
Bulk density (lb/ft^3)	69.0	46.5
Compacted bulk density (lb/ft^3)	78.0	53.0

* Ref. 135

[†] High carbon containing fines resulting from coal-cleaning operations, often impounded in slurry form behind the bank

Transportation of coarse wastes is accomplished primarily by truck, often supplemented with conveyors, trains, or aerial tramways. Slurried fines can be transported either by truck or pipeline to the disposal pond.

Waste spreading and compacting operations are typically accomplished using bulldozers. Compaction serves both to reduce pollutant migration and improve the base for soil cover.

Site reclamation entails the spreading and compacting of a soil cover, followed by planting. The soil is cultivated and seeded with a combination of grasses and legumes. Much research has been devoted to determining the plant species with the best survival rates.

Other disposal methods under investigation include hydraulic backfilling of mine voids, coal reclamation from culm piles, and waste utilization as a construction material. Of these methods, only coal reclamation is presently practiced on a large scale. Wastes generated years ago by inefficient techniques can contain up to 30 percent coal. Coal wastes can be used as asphalt concrete aggregate, admixture in cement for mine stoppings, and landfill material for purposes other than strip mine backfill. Implementation has been slow due to long distances between sources and potential markets. The use of coal wastes for mine subsidence control is being studied by the Bureau of Mines; preliminary cost estimates are higher than for other disposal methods, but may be justified where control is required.

Regulation of Coal Refuse Disposal--

Several environmental problems are associated with coal waste disposal, including ponds, fires, and groundwater contamination from leaching of acid pile runoff or pond water.

Acid runoff from the culm piles is collected in drainage sluices and neutralized prior to discharge. Regulations usually apply to effluent pH, suspended solids and iron concentrations.

Both dike construction and coal waste pile configurations are standardized in federal and state regulations and Bureau of Mines guidelines. Particular attention has been given to dike construction, as several catastrophic failures have occurred as a result of haphazard specification of dike materials. The Bureau of Mines has published research for specifying construction materials and trouble-shooting existing impoundments (Ref. 15, 86). Dike construction guidelines are identical to those for acid mine drainage ponds covered in the previous subsection of this report entitled "Acid Mine Drainage."

Federal regulations regarding safety standards for coal waste piles were developed and proposed by MESA. These regulations stipulate that:

- Compacted layers should not exceed 2 ft in thickness nor have a slope exceeding 2 horizontal to 1 vertical;

- The foundation is to be free of material that may contribute to structural instability.

Also included are general reclamation guidelines (Federal Register 40(175)).

States that have implemented regulations governing the disposal of coal wastes include Alabama, Georgia, Kentucky, Maryland, Pennsylvania, Ohio, Oregon, Tennessee, Iowa, and West Virginia.

The contamination of groundwater from tailings pond seepage or percolation has been studied, particularly with regard to certain heavy metals and pH (Ref. 86). Few of the above-mentioned states require groundwater monitoring at pond sites. Nonetheless, research is under way to reduce the permeability of mine tailings and thereby reduce the degree of pollutant mobility.

Coal Ash

Two types of ash are generated from the combustion of coal: fly ash, which is suspended in the flue gas; and bottom ash, which accumulates in the bottom of the furnace. The ratio of fly ash to bottom ash is determined primarily by the type of combustion equipment used; the total quantity of ash is a function of the fuel used.

The character of coal ash was discussed in detail in Section III and will only be summarized here. Variations in ash composition are normally attributed to coal composition, degree of pulverization, types of furnace, and certain boiler operating parameters such as temperature. Table 50 illustrates the range of ash composition commonly encountered.

Whether the various elements are entrained in the fly ash or bottom ash is specific to each element and to the combustion equipment employed. Coal ash is composed primarily of silica, alumina, and iron oxide, none of which is volatilized under normal combustion temperatures; their presence in the fly ash is due primarily to the force of the underfire air. Volatile trace metals and their oxides condense on fly ash and are collected from the exhaust gases, while other less volatile trace metals are accumulated in the molten slag and bottom ash.

Fly ash generated by utilities is collected by mechanical collectors, electrostatic precipitators (ESP), and scrubbers. The mechanical collectors, such as cyclones, generally precede the ESP and serve to collect the larger particulates (>10μ) at

TABLE 50.* POWER PLANT COAL ASH COMPOSITIONS

Constituent	Percent by Weight
Silica (SiO_2)	30-50
Alumina (Al_2O_3)	20-30
Ferric Oxide (Fe_2O_3)	10-30
Lime (CaO)	1.5-4.7
Potassium Oxide (K_2O)	1.0-3.0
Magnesia (MgO)	0.5-1.1
Sodium Oxide (Na_2O)	0.4-1.5
Titanium Dioxide (TiO_2)	0.4-1.3
Sulfur Trioxide (SO_3)	0.2-3.2
Carbon (C) and volatiles	0.1-4.0
Boron (B)	0.1-0.6
Phosphorus (P)	0.01-0.3
Uranium (U) and Thorium (Th)	0.0-0.1

*Ref. 135

efficiencies in excess of 90 percent. ESP's collect the remaining fly ash in many instances at 99+ percent efficiency. Depending on the relative collection efficiencies, the mechanical collector may retain a higher percentage of the fly ash yet less of the condensed trace elements than retained by the ESP. This occurs because the trace metals are often more concentrated in the smaller fly ash which has a greater specific surface area.

An estimated 2 to 5 percent of fly ash is normally water-soluble, depending on the presence of alkaline constituents such as lime. The physical properties of fly ash are somewhat unpredictable; compacted permeability is normally on the order of 10^{-6} cm/sec, while compressive strength and settleability are similar to that of soil. Fly ash is also pozzolanic, producing a cementitious reaction with lime and water.

Bottom ash is composed primarily of silica, alumina, and iron oxide. "True" bottom ash accounts for about 10 percent of all utility coal ash and is produced in dry bottom boilers. Boiler slag, as differentiated from bottom ash, possesses much the same chemical composition. The differences are due to wet bottom collection, which gives boiler slag a lower porosity and higher specific gravity than bottom ash.

Coal Ash Disposal--

The disposal of fly ash, bottom ash, and slag can be accomplished through ponding, landfill, or utilization. In ash ponding, the ash slurry enters one end of a pond basin and flows to the other end while allowing the ash particles to settle out. Assuming the quantity of soluble elements is low, the supernatant can be discharged to surface waters. Staged settling ponds are sometimes used to improve ash particle removal efficiencies.

The choice of ponding over other disposal methods is often contingent upon land availability. For a 1000-MW plant, the pond area required is about 100 ha at a 3-m depth (Ref. 92). The pond must also be near enough to the plant to permit piping, since truck transport of slurried ash is generally not cost competitive with landfilling dry ash. Pond liners, although not required at the present time, may eventually become an added cost consideration.

The use of a landfill to dispose of coal ash is common practice for both utility and industrial boilers. Proximity requirements are not as important, since the ash is generally transported in the dry state by truck. The potential for leachate formation in ash landfilling is unknown. Although no evidence of groundwater contamination could be found in the literature, laboratory studies have demonstrated the potential mobility of certain trace contaminants such as sulfate, chloride, boron, phosphorus, and zinc.

A variety of utilization schemes have been proposed and/or implemented for coal ash. Fly ash is presently used as a concrete additive for various construction purposes. Most of the skyscrapers constructed in Chicago during the last decade utilized concrete containing fly ash. Boiler slag and bottom ash have found use primarily as fill materials for applications such as road beds and structural fill. However, it was estimated that only 9 percent of all combustion by-products generated in the U.S. during 1969 were used for any beneficial purpose. By comparison, Britain and France reused over 40 percent of their combustion by-products (Ref. 116).

Regulation of Coal Ash Disposal--

Discharge of the clarified coal ash pond effluent is commonly practiced at power plants. Those that operate under an NPDES permit are required to monitor the effluent for TSS, heavy metals (As, Cr, Cu, Fe, Pb, Hg, Ni, Se, Zn), pH, and oil and grease.

Coal ash is considered in many states to fall into the category of solid waste and, therefore, is subject to groundwater monitoring requirements exercised in those states. Details on these requirements were presented in an earlier subsection entitled Solid Waste Disposal.

WASTEWATER DISPOSAL

All states currently operate a water quality standards program for surface waters, which is used as a basis for issuance of discharge permits. These standards would only be applicable to FGD sludge liquors if they were discharged to a surface water. The liquor constituents and their respective maximum concentrations according to these standards are discussed below.

Dissolved Oxygen (DO)

Recommended EPA standards for dissolved oxygen are based on the type of aquatic biota existing in the waters. State standards recommend a minimal 5 mg/ℓ DO concentration for freshwater biota for warm water species, and a minimal 5 to 6 mg/ℓ DO concentration (7 mg/ℓ at spawning times) for cold water biota. A minimum of 6 mg/ℓ is recommended for small inland lakes or for large lakes that have insufficient mixing of constituent layers. For saltwater organisms, minimal DO levels of 5 mg/ℓ are recommended in the open coastal waters and 4 mg/ℓ in the estuarine and tidal tributaries.

The dissolved oxygen criteria for all states fall between 2.0 mg/ℓ and 8 mg/ℓ, although some states limit dissolved oxygen by saturation, with limits ranging from 50 to 90 percent.

pH and Acidity/Alkalinity

All state pH limits fall between 5.0 and 10.0, with the majority falling between 6.0 and 9.0. Some states limit pH by deviation from the naturally occurring pH of the water. Only Delaware has limits for alkalinity (20 to 80 mg/ℓ) and acidity (5 mg/ℓ) both as $CaCO_3$.

Suspended and Other Particulate Solids

EPA published an "Example Water Quality Standard" that is followed closely by the states. General criteria recommended by EPA are as follows:

> All surface waters shall meet the generally accepted aesthetic qualifications and shall be capable of supporting desirable diversified aquatic life, and these waters shall be --
>
> 1. Free from substances attributable to municipal, industrial, or other discharges or agricultural practices that will settle to form objectionable sludge deposits.
>
> 2. Free from floating debris, scum, and other floating materials attributable to municipal, industrial, or other discharges or agricultural practices in amounts sufficient to be unsightly or deleterious.
>
> 3. Free from materials attributable to municipal, industrial, or other discharges or agricultural practices producing color, odor, or other conditions in such degree as to create a nuisance.
>
> 4. Free from substances attributable to municipal, industrial, or other discharges or agricultural practices in concentrations or combinations which are toxic or harmful to human, animal, plant, or aquatic life.

This, or similar wording is found in all state regulations.

The Alaska Wastewater Disposal Regulations (Adm. Code, Title 18, Chapter 72) require written permission for subsurface disposal:

> No person may discharge sewage or industrial liquid waste into the ground by well, crevice, sinkhole, gravel pit or depression, or any other opening, whether natural or manmade, without written approval from the department.

The West Virginia regulations, Section 17, Water Purification Wastewater Control Measure, stipulate certain pond design standards that might be applied to FGD sludge ponds:

1. Lagoon design must provide the following:

    a. Location free from flooding.

    b. Dikes, deflecting gutters or other means of diverting surface water when necessary.

    c. A minimum depth of 4 to 5 feet.

    d. Multiple cell.

    e. Adjustable decanting devices.

    f. Convenient cleaning.

Heavy Metals

Many states restrict toxic substances by narrative statement. A few restrict toxic substances by median tolerance limit, e.g., not to exceed 1 mg/ℓ of the 48-hr TLm. Many states limit heavy metals by elements for some or all of the water-use classes. Typical limits follow:

	Concentration mg/ℓ
Arsenic	.05
Barium	1.0
Cadmium	.01
Chromium (total hexavalent)	.05
Copper	(range: .01-1)
Iron	.3
Lead	.05
Selenium	.01
Silver	.05

For surface waters used as public drinking water supply, the following constituent limits are often also limited.

Cyanide	.02-.2
Fluoride	1.0

The following typical narrative statement is excerpted from the Nevada Water Quality Standards, Article 4(4.1f):

> f. No wastes from municipal or industrial or other controllable sources containing arsenic, barium, boron, cadmium, chromium, cyanide, fluoride, lead, selenium,

silver, copper and zinc that are reasonably amenable to treatment or control will be discharged untreated or uncontrolled into the waters of Nevada. In addition, the limits for concentrations of the chemical constituents will provide water quality consistent with the mandatory requirements of the 1962 Public Health Service Drinking Water Standards.

WATER QUALITY CRITERIA FOR VARIOUS BENEFICIAL USES

Federal Water Quality Control Laws: Surface Waters

The Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500) established the framework for water quality control laws and regulations used by the various states. Under this law, the states retain the primary responsibility for water quality protection. However, the U.S. EPA is authorized to intervene if the states do not enforce the law. The relevant elements of Public Law 92-500 are the water quality standards program, the NPDES program, treatment requirements, and the effluent guidelines.

Water Quality Standards Program--

All states administer a water quality standards program wherein the surface waters of the state are categorized by beneficial uses, e.g., drinking water supply, recreation, fish and wildlife, agricultural, industrial, etc. For each class of water use, narrative and/or numerical limits are established for various parameters, such as dissolved oxygen, pH, temperature, and turbidity. The parameter limits are to be maintained in the receiving water to protect its beneficial uses. The important distinction here is that the limits are upon the receiving water - not upon the discharges to it.

NPDES Program--

All discharges to navigable waters require an NPDES permit. These permits are issued by the EPA and by states that are delegated the authority by EPA. An NPDES permit can stipulate any of the following: effluent limitations, maximum flow, monitoring requirements, schedule of compliance, operation and maintenance requirements, etc. In the case of FGD sludges, if overflow from a scrubber sludge pond is discharged into a surface water, an NPDES permit is required.

Treatment Requirements--

Regarding required treatment for control of water pollution, Public Law 92-500 states:

- Industries must use the "best practicable" technology to control water pollution by July 1, 1977, and the "best available" technology by July 1, 1983.

- Publicly owned waste treatment plants must provide a minimum of "secondary treatment" by July 1, 1977, and must apply the "best practicable" technology by July 1, 1983.

Effluent Guidelines--
EPA has established national effluent limitations and performance standards for many industrial waste sources. However, no standards have been promulgated as yet for the scrubber sludges from power plants.

Federal Drinking Water Standards

EPA is authorized by the Safe Drinking Water Act of 1974 to establish interim primary drinking water standards. Table 51 shows the maximum contaminant levels for various inorganic chemicals as specified by the interim standards promulgated in December 1975.

Federal Irrigation Water Standards

The regulation of irrigation water quality must take into consideration the short-term effects on crop quality, long-term effects on soil characteristics and surrounding groundwaters, and the intended utility of the crop. Water classified as irrigation water is generally applied to (1) agricultural crops, (2) pasture land, (3) turf and landscape, and (4) stock watering. Absolute limits on irrigation water are difficult to establish due to a number of site-specific factors, e.g., soil type, climate, irrigation practices, etc.

Table 52 presents general limits for irrigation water constituents as suggested by the U.S. EPA for both short-term and extended (over 20 years) use. Many of the allowable contaminant concentrations are several times higher than those allowed by the drinking water standards (examples: arsenic, chromium, lead, and selenium; constituents such as mercury are not listed in the irrigation standards).

State Groundwater Protection Regulations

In nearly all cases, the state regulatory agencies are authorized to protect both surface and subsurface waters, e.g., to prevent degradation of groundwater. However, only a few states have specific criteria for groundwater protection. The Maryland Groundwater Quality Standards (Reg. 08.05.04.04), for example, identify three types of underground aquifers - types I, II, and III - based on transmissivity, permeability, and total dissolved solids concentration of the natural water. The following limitations are established for each type:

TABLE 51.* NATIONAL INTERIM PRIMARY DRINKING WATER REGULATIONS--MAXIMUM CONTAMINANT LEVELS FOR INORGANIC CHEMICALS

Contaminant	Level (mg/ℓ)
Arsenic	0.05
Barium	1.
Cadmium	0.010
Chromium	0.05
Fluoride	†
Lead	0.05
Mercury	0.002
Nitrate (as N)	10.
Selenium	0.01
Silver	0.05

* Federal Register, p 59570, December 24, 1975

† Fluoride is regulated as a function of average daily maximum air temperature:

Air Temperature (°C)	Fluoride Level (mg/ℓ)
12.0	2.4
12.1-14.6	2.2
14.7-17.6	2.0
17.7-21.4	1.8
21.5-26.2	1.6
26.3-32.5	1.4

TABLE 52.* LIMITS OF POLLUTANTS FOR IRRIGATION WATER RECOMMENDED BY EPA

Constituents	For Water Used Continuously on all Soils (mg/ℓ)	For Short-Term Use[†] on Fine Textured, Neutral, and Alkaline Soils (mg/ℓ)
Heavy Metals		
Aluminum	5.0	20.0
Arsenic	2.0	10.0
Beryllium	0.1	0.5
Boron	0.75	2.0
Cadmium	0.01	0.05
Chromium	0.1	1.0
Cobalt	0.05	5.0
Copper	0.2	5.0
Fluoride	2.0	15.0
Iron	5.0	20.0
Lead	5.0	10.0
Lithium	2.5	-
Manganese	0.2	10.0
Molybdenum	0.01	0.05
Nickel	0.2	2.0
Selenium	0.02	-
Bacterial		
Coliform density	1,000/100mℓ	
Chemical		
pH	4.5-9.0	
TDS	5,000	
Herbicides		
Dalapon	0.2 µg/ℓ	
TCA	0.2 µg/ℓ	
2,4-D	0.1 µg/ℓ	

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* Ref. 134

[†] Short-term used here means a period of time as long as 20 years

1. Type 1 Aquifers

The characteristics of constituents of waters or wastewaters discharged into Type 1 Aquifers may not exceed, or cause the natural groundwater quality to exceed, mandatory or recommended standards for drinking water as established by the Federal Government.

2. Type II Aquifers

The characteristics or constituents of waters or wastewaters discharged into Type II Aquifers may not exceed or cause the natural groundwater quality to exceed receiving (surface) water quality standards as established for Class I Waters by the State. In addition, the person responsible for the discharge shall provide the Water Resources Administration with evidence that the discharge will not result in pollution of Type I Aquifers.

3. Type III Aquifers

The characteristics or constituents of waters or wastewaters discharged into Type III Aquifers shall be identified to the Water Resources Administration, and evidence shall be provided to assure the Water Resources Administration that there will not be pollution of either Type I or Type II Aquifers or surface waters, and that the public health and welfare will not be endangered as a consequence of such disposal.

According to the New York Groundwater Classification and Standards (Part 703):

a. The ground waters of the State are classified according to best use, and all fresh ground waters are best used as sources of potable water supply. Such fresh waters, when subjected to approved disinfection treatment and/or additional treatment to reduce naturally present impurities to meet New York State Health Department drinking water standards, are deemed satisfactory for potable purposes.

Contaminant limits established in New York for groundwaters to be used as potable water supply are shown in Table 53.

Missouri has Regulations for Ground Water Recharge and Irrigation Return Water, shown below:

This section shall apply to percolating water from all areas of land on which wastes or wastewater is applied or allowed to accumulate whether or not additional treatment is to be obtained by application to the land. Such percolating water shall be considered an effluent to the subsurface

TABLE 53.* STATE OF NEW YORK GROUNDWATER CONTAMINANT LIMITS

Substance	Concentration in mg/ℓ Schedule I	 Schedule II
Alkyl benzene sulfonate (ABS)	1.5	1.0
Arsenic (As)	0.1	0.05
Barium (Ba)	2.0	1.0
Cadmium (Cd)	0.02	0.01
Carbon chloroform extract residue (CCE)	0.4	0.2
Chloride (Cl)	500	250
Chromium (hexavalent) (Cr^{+6})	0.10	0.05
Copper (Cu)	0.4	0.2
Cyanide (CN)	0.4	0.2
Fluoride (F)	3.0	1.50
Iron (Fe)	0.6	0.3
Lead (Pb)	0.10	0.05
Manganese (Mn)	0.6	0.3
Nitrate (N)	20.0	10.0
Phenols	0.002	0.001
Selenium (Se)	0.02	0.01
Silver (Ag)	0.10	0.05
Sulfate (SO_4)	500	250
Total dissolved solids	1000	500
Zinc	0.6	0.3
pH†	6.5-8.5	6.5-8.5

* New York State Groundwater Classifications and Standards (Part 703)

† When natural groundwaters have a pH outside of range indicated above, the natural pH may be one extreme of the allowable range

> "Waters of the State" when it reaches a depth of more than 4 feet or is within 12 inches of bedrock if such bedrock occurs at depths of less than 5 feet, and shall be subject to the following requirements. Percolating water which is intercepted by either natural or artificial means and reappears on the surface shall be considered indirect release to surface "Waters of the States. . ."

The specific requirements for Missouri state groundwater contaminant limits are shown in Table 54.

Kansas has Underground Storage Regulations that require a permit for all surface ponds. The regulations apply as follows:

> This article regulates the construction and use of underground storage reservoirs and the construction and use of disposal wells and surface ponds for the confinement, storage and disposal of industrial fluids including but not limited to brines, but does not include regulations pertaining to oil field activities described in L 1965, Ch. 506, Sec. 1(4)p.

The Kansas Regulations also state the following regarding operation and maintenance:

> Operators of underground reservoirs shall maintain a permanent record of the type and quantity of all products stored there, and a continuous record of the injection pressures, and shall report immediately to the chief engineer for the state board of health any failures or defects in the underground reservoir.

The Idaho regulations have a section on Land Treatment and/or Disposal of Wastewater(s), shown below:

> Land treatment and/or disposal of liquid waste material(s) requires that
>
> . . . Provision shall be made for monitoring the quality of the ground water in proximity of the disposal area. All data and reports resulting from the ground water monitoring program will be submitted to the Department upon request. The minimum frequency of monitoring and data submittal will be dependent upon the nature and volume of wastewater material, the frequency and duration of disposal, and the characteristic of the soil mantle on the disposal site.
>
> 3. Land treatment and/or disposal shall not create a ground water mound or result in a salt build-up on another person's property.

TABLE 54.* STATE OF MISSOURI GROUNDWATER CONTAMINANT LIMITS

Contaminant	Maximum Value Allowed
Arsenic	50 µg/ℓ
Barium	1,000 µg/ℓ
Cadmium	30 µg/ℓ
Chromium (total)	500 µg/ℓ
Copper	20 µg/ℓ
Cyanide	10 µg/ℓ
Fluoride	1,200 µg/ℓ
Lead	50 µg/ℓ
Nickel	800 µg/ℓ
Phenols	5 µg/ℓ
Selenium	10 µg/ℓ
Silver	50 µg/ℓ
Zinc	100 µg/ℓ
COD	10 mg/ℓ
Threshold Odor Number (TON)	3
Linear Alkylate Sulfonates	1.0 mg/ℓ
Chlorides	250 mg/ℓ
Sulfates	250 mg/ℓ
Total dissolved solids	500 mg/ℓ
Nitrate as (NO_3)	10 mg/ℓ
Heavy metal ratio shall not exceed 1.00+	

$$+\ \frac{Cu}{20} + \frac{Zn}{100} + \frac{Pb}{50} + \frac{Cr}{500} + \frac{Cd}{30} + \frac{Ni}{800} = 1.00$$

Where the abbreviation for the metal in the fraction is the measured concentration in the effluent in micrograms per liter (µg/ℓ)

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* Missouri: Groundwater Recharge and Irrigation Return Water (Appendix II)

4. Land treatment and/or disposal shall not create a public health hazard, a nuisance condition, or an air pollution problem.

The Michigan Liquid Industrial Waste Disposal Act governs the methods of disposal of liquid industrial wastes, including licensing of persons and vehicles. It states the following regarding disposal:

> . . . The licensee shall not dispose of wastes onto or into the ground except at locations specifically approved by the commission . . . No waste shall be placed in a location where it could enter any public or private drain, pond, stream or other body of surface or ground water.

AIR POLLUTION REGULATIONS

With the promulgation of the New Source Performance Standards (NSPS) for Fossil Fuel-Fired Steam Generators (40 CFR, Part 466, 8/17/71), wet lime/limestone scrubbers became the anticipated "best method" of removing SO_2 from the flue gas of a power plant. NSPS confessed to the problem of sludge disposal, yet placed it on a hazard level similar to that of fly ash.

The NSPS were remanded to EPA by a U.S. Court of Appeals in 1973, with one of the allegations involving insufficient EPA consideration of the sludge disposal problem. The court decision stated that the record be remanded for further "consideration and explanation . . . of the adverse environmental effects of requiring a 1.2 lbs/million BTU standard for those . . . plants which must use a lime slurry scrubbing system . . ."

In its Draft Response to Remand (40FR 42045), EPA concluded that the standards should not be revised to account for sludge disposal. It was noted, however, that "EPA considers permanent land disposal of raw sludge to be environmentally unsound, because it definitely degrades on large quantities of land" (Section C.I.(c)). As an acceptable solution, both fixation and alternate control systems that do not generate sludge are considered acceptable. The response states that "fixation of the sludge will greatly reduce its environmental impact," as it has a "much lower leachability" than untreated sludge, "and the leachates . . . are potentially less of a disposal problem than (those) from fly ash."

It was also suggested in the Draft Response to Remand that some plants that must postpone fixation utilize lined holding ponds for temporary storage. Permanent disposal of raw sludge in any type of pond, however, is not considered acceptable due to the indefinite degradation of large quantities of land.

Although the Draft Response to Remand is not to be construed as regulation, it was nonetheless apparent that EPA views sludge fixation as the best available technology for FGD sludge disposal.

While many of the state SO_2 emission regulations are at least as stringent as the federal regulations, it could not be determined from the literature which states have included sludge disposal recommendations as part of the standard.

WASTE DISPOSAL TO OCEANS

The Marine Protection, Research and Sanctuaries Act of 1972 (Public Law 92-532) has been the basis for domestic control of ocean dumping. The act removes ocean dumping regulation from state, interstate, or regional authorities and consolidates control under the administrator of the federal EPA (Sec. 104 (d)). The administrator may issue permits for ocean disposal after:

1. Determining "that such dumping will not unreasonably degrade or endanger human health, welfare, or amenities, or the marine environment, ecological systems, or economic potentialities," or,

2. Applying criteria established expressly for reviewing and evaluating such permit applications. These criteria shall include but not be limited to the following:

    a. The need for the proposed dumping.

    b. The effect of such dumping on human health and welfare, including economic, aesthetic, and recreational values.

    c. The effect of such dumping on fisheries resources, plankton, fish, shellfish, wildlife, shore lines and beaches.

    d. The effect of such dumping on marine ecosystems, particularly with respect to -

        i. the transfer, concentration and dispersion of such material and its by-products through biological, physical, and chemical processes,

        ii. potential changes in marine ecosystem diversity, productivity, and stability, and

        iii. species and community population dynamics.

e. The persistence and permanence of the effects of the dumping.

f. The effect of dumping particular volumes and concentrations of such materials.

g. Appropriate locations and methods of disposal or recycling, including land-based alternatives and the probable impact of requiring use of such alternate locations or methods upon considerations affecting the public interest.

h. The effect on alternate uses of oceans, such as scientific study, fishing, and other living resource exploitation, and nonliving resource exploitation.

i. In designating recommended sites, the Administrator shall utilize wherever feasible locations beyond the edge of the Continental Shelf.

3. Determining that no applicable water quality standards will be violated (Sec. 102 (a));

4. Consulting with federal, state, and local officials, and interested members of the general public, as may appear appropriate to the Administrator when establishing or revising such criteria.

The act specifies that any feasible disposal alternatives should be considered in lieu of ocean disposal. Consequently, the regulatory environment is not presently conducive to ocean disposal of FGD sludges.

The Key West Utility Board Stock Island Plant occasionally discharges sludge pond supernatant directly into the Gulf of Mexico. This practice is currently regulated by an NPDES permit and Florida State Industrial Waste guidelines. The Marine Protection, Research and Sanctuaries Act has not been adapted to regulate this effluent.

WASTE DISPOSAL TO MINES

There are currently no state or federal regulations that relate specifically to the disposal of FGD wastes to mines. Regulations that apply indirectly to mine disposal include:

- Waste disposal
- Water quality
- Health and safety

The specific applicability of these regulations to FGD sludge disposal to mines is currently under study by Arthur D.

Little, Inc. under contract to EPA. A discussion of waste disposal regulations and water quality criteria as they relate to FGD sludge disposal was presented earlier in this report.

For mine disposal operations where use of some type of impoundment structure is indicated, the Dam Safety Act (Public Law 92-367) regulates impoundment construction and monitoring. However, where no dam is necessary, no statutes require consideration of catastrophic release of desulfurization wastes or any wastes from mine disposal.

The law states that the Secretary of the Army shall determine "whether a dam constitutes a danger to human life or property." Furthermore, he "shall take into consideration the possibility that the dam might be endangered by overtopping, seepage, settlement, erosion, sediment, cracking, earth movement, earthquakes, failure of bulkheads, flashboard, gates on conduits, or other conditions which exist or which might occur in any area in the vicinity of the dam" (Sec. 4). This could be interpreted to regulate FGD sludge mine disposal.

To be regulated by this law, the impoundment must either be greater than 6 ft in height, or have a storage capacity greater than 15 ac-ft (Sec. 1). Certain mine disposal operations may not be regulated by the Dam Safety Act because of this requirement.

Transportation of various materials similar to desulfurization sludge is effectively regulated. By interpretation, the Hazardous Materials Transportation Act of 1970 could adequately regulate FGD sludge transportation to mine disposal sites. The act defines hazardous materials as: "substances or materials in a quantity and form which may pose an unreasonable risk to health and safety or property when transported in commerce" (Public Law 91-458).

Protection of health and safety appear to be subject to adequate regulation by various Mining Enforcement and Safety Administration (MESA), and Occupational Safety and Health Administration (OSHA) standards and guidelines. Protection can be accomplished by adaptations of the existing statutes. These are:

a. Materials shall be stored and stacked in a manner which minimizes stumbling or fall-of-material hazards.

b. Materials that can create hazards if accidently liberated from their containers shall be stored in a manner that minimizes the dangers.

c. Hazardous materials shall be stored in containers of a type approved for such use by recognized agencies; such containers shall be labeled appropriately. (MESA, Guideline 77.208)

No person shall be permitted to walk or stand immediately above a reclaiming area or in any other area at or near a surge or storage pile where the reclaiming operation may expose him to a hazard. (MESA, Guideline 77.209)

CASE STUDY: THE COMMONWEALTH OF PENNSYLVANIA*

In Pennsylvania, the Commonwealth's Solid Waste Management Program (hereafter referred to as "the Program") has primary responsibility for regulating the disposal of FGD sludges; this responsibility is based upon the Pennsylvania Solid Waste Management Act 241. Because permits must be obtained in other regulatory jurisdictions, the Program coordinates its activities with the Water Quality Management Program within the Pennsylvania Department of Environmental Resources.

Since 1972, the Program has permitted sludge disposal operations at three power plants in the Commonwealth: the Duquesne Light Company Phillips and Elrama stations, and the CAPCO Bruce Mansfield Station. Initially, the Program took a passive role. Lacking FGD sludge data and experience, their role was to monitor the experimental work being performed at the Phillips station and to keep abreast of related research nationwide. However, the design and construction of the Bruce Mansfield Power Station obligated the Program to review the various proposals for FGD sludge management and formalize the evaluation criteria required of applicants.

Evaluation Criteria

Disposal system evaluation criteria were developed by the Solid Waste Management and Water Quality Management Programs jointly. The approach taken was to evaluate each proposed treatment process and site design individually for its potential environmental impact. It was decided that the most important evaluation criteria were:

- Potential for ground and surface water pollution
- Nuisance prevention
- Proper dam construction, and
- Site reclamation

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*Personal communication with Gary Merritt, Pennsylvania Department of Environmental Resources, February 22, 1977.

In order to best employ these criteria when evaluating a potential disposal operation, three basic areas of analysis were proposed:

- Product (or waste) characteristics;
- Storage (or disposal) site characteristics; and
- Operating requirements.

Product (Waste) Characteristics--

Of major concern is the potential contamination of ground and surface waters in the vicinity of storage and disposal areas. A secondary concern is the physical characteristics of the material which will control its engineering use. The information required for an evaluation of these concerns is:

- Chemical and physical analyses of the materials;
- Potential for generating leachates; and
- Character of the leachate with respect to total dissolved solids and heavy metals.

Physical characteristics such as triaxial strengths, permeability, moisture content compaction, and particle size distribution are needed to determine the stability and design of any site.

Storage (or Disposal) Site Characteristics--

Site characteristics of interest from an environmental standpoint include local hydrology, geology, topography, and meteorology. Evaluation criteria must take into account the interaction of these factors and their effect on the environment. Since the criteria are site-specific, only general considerations can be addressed. The single most critical element of the site is its hydrogeologic characteristics. These will dictate the design and possible limitations on the use of the site due to potential ground and surface water pollution.

Operating Requirements--

Operating plans will be assessed for possible environmental impact. Activities of interest include truck routes and frequency of travel, pipeline right-of-way, placement of sludge at the landfill, and operation of the pond. Also, possible fugitive dust emissions must be accounted for. Completed site characteristics and projected land use must be assessed.

Regulation of the Bruce Mansfield Disposal Operation

The CAPCO Bruce Mansfield Power Station, located in Shippingsport, Pennsylvania, is a 2,700 MW, three-unit, coal-fired plant. Unit 1 began operation in December, 1975; units 2 and 3 are expected to begin commercial operation in October

1977 and October 1979 respectively (Ref. 34, 40). During the design of the Bruce Mansfield FGD sludge disposal operation, two methods of commercial stabilization were proposed: those offered by I U Conversion Systems and the Dravo Corporation (see Section VII). The disposal of raw sludge and non-commercially stabilized sludge was not considered.

Permit Procedures--

The permitting procedure for land disposal of FGD wastes is governed by three pieces of Pennsylvania legislation: the Solid Waste Management Act, the Water Obstructions Law, and the Clean Streams Law. Because of the variety of environmental considerations involved in selecting and operating a disposal site, the legislation mandates coordination of water quality and solid waste activities between the associated programs.

The Solid Waste Management Act provides for the issuance of solid waste disposal permits. These permits are required for the disposal of any solid waste on land. The first phase of the two-phase procedure involves (1) the submittal of chemical and physical data on the sludge characteristics, and (2) a detailed hydrogeologic study of site conditions. Phase II consists of a detailed review of the system engineering, including specifics of design, operation, and end use.

The Clean Streams Law provides for the issuance of three permits in the water quality area:

- Industrial Wastes Discharge Permit;
- Sedimentation and Erosion Control Permit; and
- Pollution Incident Prevention Plan (PIPP).

The Industrial Wastes Discharge Permit applies to liquid discharges to surface waters of the state. Standards include (1) state effluent discharge limitations, and (2) standards of quality established for each stream. The discharge from an FGD sludge disposal site must conform to the most stringent of these standards, although some flexibility is allowed for certain streams. The Sedimentation and Erosion Control Permit requires that a formal plan for sedimentation and erosion control around the disposal area be developed. This plan is submitted to the Soil Conservation Service for final approval. A PIPP involves the identification of potential pollution problems and the submittal of a plan to deal with them should they arise. The identification of problem areas is the responsibility of the owner or operator.

The Water Obstructions Act applies to any activities which alter the existing surface waters or provide for new waterways. The permits provided for under this act include:

- Encroachment permits; and
- Dam construction permits.

An encroachment permit is required when (1) a waterway is dammed up and allowed to encroach upon adjacent land, or (2) the path of a waterway is altered. A detailed hydrologic study of the surrounding area is required. The dam construction permit is an engineering evaluation of a proposed dam, evaluating test borings and construction monitoring, as well as the specification of safety factors.

It must again be emphasized that the successful implementation of these permitting procedures require coordination between the various environmental programs.

Discussions between Program officials and I U Conversion Systems concerning their process and conceptual approach to managing the flue gas desulfurization sludges were held in late 1972. The IUCS process produces a product that is both stable for disposal and useful in a variety of structural applications. The proposed disposal methods were backfilling of abandoned surface mines and use as embankment fill. It was decided that either method would require permitting.

The permits required for the disposal of the sludge processed using the IUCS process would be dependent upon which disposal concept was selected. If the backfilling of abandoned surface mines were chosen, then two permits (and a PIPP) would be required: a Solid Waste Disposal Permit and a Sedimentation and Erosion Control Permit. If the sludge were to be used as an embankment fill, four permits (and a PIPP) would be required: a Solid Waste Disposal Permit for any discharge from the pond; a Sedimentation and Erosion Control Permit; and depending upon the size of the drainage basin, perhaps an Encroachment Permit.

Discussions with Dravo concerning their proprietary process and conceptual approaches to disposal of the Bruce Mansfield FGD sludges were held in late 1972. Their conceptual approach involved treatment with a proprietary process, followed by pipeline transport of the wet slurry to the final disposal site. The disposal area was to consist of a dam located near the base of a valley. There, scrubber sludge would be discharged to settle and harden (under water) in place behind the dam. Collected wastewater would be returned to the scrubber cycle as make-up water.

Under Dravo's proposal, four permits and an approved PIPP program would be required. The permits would include a Solid Waste Disposal Permit, a permit for the construction of a dam, an Industrial Waste Permit for any discharges to surface waters, and a Sedimentation and Erosion Control Permit. The Dravo concept, as stated above, was eventually selected. The Little

Blue Run impoundment area will eventually occupy 1,300 ac behind a 420 ft impoundment structure. As the impoundment area will eventually straddle the Pennsylvania-West Virginia border, permits were required from both states.

Evaluation of Potential Water Quality Impacts--
In the process of evaluating the above permit applications, the Solid Waste Management Program conducted leaching tests on samples of materials processed by Dravo and IUCS. The leaching methodology used for the sludge samples consisted of the following tests:

- Mix 500 gr of solid processed sludge with 2,000 ml of deionized distilled water;
- Agitate the mixture continuously for a minimum of 48 hours;
- Pass the supernatant through a filter (#42); and
- Analyze the filtrate.

The tests were performed on both raw sludges and sludges stabilized by the Dravo and IUCS processes. In addition, as a basis for comparison, tests were performed on fly ash, bottom ash, and Basic Oxygen Furnace (BOF) slag.

Based upon the results of those tests, Program officials concluded that leaching from neither raw nor stabilized sludge would present a hazard to the environment. The leaching tests presented an extreme leaching environment, but few of the metals analyzed in the leachate exceeded drinking water standards. Furthermore, the elutriates were superior in quality to most of the fly ash leachate samples.

Conclusions

The Solid Waste Management Program, based upon their findings during the Bruce Mansfield investigation, compared FGD sludge disposal to the disposal of other solid and liquid wastes. In particular, they compared the leaching results to various leachates from other waste products (coal ash, fly ash, and basic oxygen furnace slag) and to existing water quality standards.

Their conclusions were as follows:

"A. The environmental problems which may result from the disposal of sludge generated by the slaked lime-wet scrubber operations will be mainly those of logistics:

(1) Tremendous volumes of sludge will be generated in relatively concentrated point sources. Large quantities of land will be required for the disposal of this waste.

(2) There may be some materials-handling problems (proper equipment, spillage, etc.) which seem to be solved by pre-processing of the sludge before disposal.

(3) Supernatant to be used as make-up water appears to be viable (comparatively low TDS) from this process.

(4) There is a possibility of a very high chemical oxygen demand from the untreated sludge if the calcium sulfite is released into the water environment."

"B. Heavy metals appear to be highly insoluble in the sludge samples tested. The pH is fairly high in every case. Ninety-eight (98) percent of the measurements of heavy metal ions are below detection limits or effluent standards.

"C. Dissolved solids and sulfates decrease considerably with the aging of the sludge" (as leaching becomes diffusion-limited)

"D. The methodology used in preparing the sample has no significant effect on the test results for heavy metal ions. However, the total dissolved solids and sulfates do show significant differences. Actual physical conditions to which the deposited wastes will be subjected will not be as turbulent (less surface area will be exposed) as that experienced in the shaking tests.

"E. The results of this study are only relevant to slaked lime-wet scrubber operation.

"F. The sample preparation methods ensured that the leachate was produced under aerobic conditions only.

"G. Heavy metals ions will not be a problem in the disposal of the sludge treated or untreated."

SECTION XII

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SECTION XIII

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SECTION XIV

GLOSSARY

ABBREVIATIONS

ac	acre
ac ft	acre feet
AMD	Acid Mine Drainage
Btu	British thermal unit
cm	centimeter
cm/sec	centimeter per second
m3	cubic meter
ft^3/sec	cubic feet per second
COD	Chemical Oxygen Demand
^oC	degrees centigrade (Celsius)
^oF	degrees fahrenheit
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ft	feet
ft/s	feet per second
FDS	Flooded Disc Scrubber
FGC	Flue Gas Cleaning
FGD	Flue Gas Desulfurization
ft	foot
gal	gallon
gpm	gallons per minute
g	gram
ha	hectare
hr	hour
IERL-RTP	Industrial Environmental Research Laboratory - Research Triangle Park
in	inches
in/s	inches per second

ABBREVIATIONS (continued)

J	Joule
J/s	Joule per second
kg	kilogram
kcal/kg	kilocalorie per kilogram
km	kilometer
kw	kilowatt
L/G	Liquid to Gas ratio
ℓ	liter
ℓpm	liters per minute
M	Mega
MW	Megawatt
MWh	Megawatt hour
MESA	Mine Enforcement and Safety Administration
mgd	million gallons per day
N	newton
No.	number
NPDES	National Pollutant Discharge Elimination System
OSHA	Occupational Safety and Health Administration
ppm	parts per million
lb	pound
psi	pounds per square inch
sec	second
SCE	Southern California Edison
m^2	square meter
TCA	Turbulent Contact Adsorber
TDS	Total Dissolved Solids
TOS	Total Oxidizable Sulfur
TPD	metric Tons Per Day
TSS	Total Suspended Solids
TVA	Tennessee Valley Authority
USDA	United States Department of Agriculture
W	Watt
WES	Waterways Experiment Station (U.S. Army, Vicksburg, Mississippi)

METRIC - ENGLISH UNIT CONVERSION TABLE

Length

1 meter = 39.37 inches - 3.28 feet = 1.09 yards
1 kilometer = 0.62 miles
1 millimeter = 0.03937 inches
1 centimeter = 0.3937 inches
1 micrometer = 3.937 x 10^{-5} inches

Area

1 square meter = 10.744 square feet = 1.196 square yards
1 square kilometer = .384 square miles = 247 acres
1 square centimeter = 0.155 square inches
1 square millimeter = o.00155 square inches
1 hectare = 2.471 acres

Volume

1 cubic meter = 35.314 cubic feet = 1.3079 cubic yards
1 cubic centimeter = 0.061 cubic inches
liter = 1.057 quarts = .0264 gallons = 0.81 x 10^{-6} acre-feet

Mass

1 kilogram = 2.205 pounds
1 gram = 0.035 ounces = 15.43 grains
1 milligram = 0.01543 grains

Velocity, linear

1 meter per second = 3.28 feet per second
1 millimeter per second = 0.00328 feet per second
1 kilometer per second = 2,230 miles per hour
1 meter per second = 2.24 miles per hour

Flow (volumetric)

1 cubic meter per second = 15,850 gallons per minute = 2,120 cubic feet per minute
1 liter per second = 15.85 gallons per minute

Viscosity

poise = 1.45 x 10^{-5} pounds (weight) seconds/square inch

Density

1 gram per cubic centimeter = 62.428 pounds per cubic foot

METRIC - ENGLISH UNIT CONVERSION TABLE (Continued)

Pressure

1 newton per square meter = 0.00014 pounds per square inch
1 newton per square centimeter = 1.4×10^{-10} pounds per square inch
1 kilogram (force) per square centimeter = 14.223 pounds per square inch
1 dyne per square centimer = 1.450×10^{-5} pounds per square inch

Temperature

1 degree Kelvin or 1 degree Celsius = $\frac{5^{o}F}{9} - 17.77$

Work, energy, quantity of heat

1 Joule = 2.778×10^{-7} kilowatt hours = 3.725×10^{-7} horsepower hours = 0.73756 foot-pounds = 9.48×10^{-4} British thermal units
1 kilojoule = 2.778 kilowatt-hours

APPENDIX A

AVAILABLE TECHNOLOGY AND REGULATORY OPTIONS

GENERAL

This section suggests an approach to the formulation of guidelines and limitations for FGC sludge management based upon best practical control technology currently available. The mechanisms for attenuation or dilution of FGD sludge contaminants under real world conditions have been evaluated both in theory and practice. The physical properties of FGD sludge have also been studied in detail. These physical and chemical properties set need for regulation.

The suggested regulatory approach is analogous to the procedures being followed by state regulatory agencies in establishing guidelines and limitations for treated wastewater point sources. Regulatory agencies in their review of proposed new wastewater treatment facilities for point source discharges go through the following steps:

1. The beneficial use of the receiving water is established, e.g., use as a trout stream, a drinking water supply, recreational body contact, etc.

2. Based upon the beneficial use established, maximum concentrations for various contaminants in the treated effluent are set, e.g., 10 mg/ℓ BOD, 3 mg/ℓ nitrogen, etc.

3. Given the effluent limitations (maximum contaminant concentrations) which must be met, the applicant responds with a treatment technology which will theoretically supply sufficient treatment to meet the effluent limitations on a sustained basis, e.g., activated sludge followed by chemical coagulation and filtration, etc. The regulatory agency reviews the pro-proposed technology.

4. Upon approval of the technology, the regulatory agency will provide the applicant with specific design criteria for use in preparing detailed

design plans and specifications, e.g., clarifier overflow rates, distance to nearest residence, etc.

5. Finally, the regulatory agency establishes monitoring, control, and reporting procedures which the applicant must implement to ensure that the effluent limitations established in No. 2 above are being met.

The above approach is site-specific, as opposed to a universally applied "one number" approach and recognizes that local site conditions are important in establishing best practical control technology. In addition, the above approach allows the applicant to make cost-effective decisions within established technical boundaries. Finally, the approach provides continuous interaction between applicant and regulatory agency to ensure that environmental protection objectives are met.

The wastewater effluent limitations approach outlined above can be adopted to FGD sludge treatment/disposal guidelines and limitations. Figure 22 shows in a simplified flow diagram the major steps involved. If each of the steps shown can be carefully defined in a procedural manner, it will provide a uniform, organized approach to decision-making based upon site/waste specific data. Each step is individually discussed in the following subsections. The reader is cautioned that the discussion is conceptual. It is recognized that substantial additional site-specific analysis is required before a comprehensive cookbook procedure can be developed that is universally applicable to all FGD disposal operations.

DEFINE BENEFICIAL USES

In this step, the regulatory agency, with the cooperation of the applicant, performs an evaluation of the proposed disposal site to determine what beneficial environmental resources require protection. The environmental factors which warrant protection during FGD sludge disposal are the following:

1. Groundwater resources underlying the site;

2. Surface water resources at elevations lower than the site; and

3. Future land uses at the site location.

Groundwater Resources

Considering first groundwater resources underlying the site, a comprehensive hydrological report is required which includes the following information:

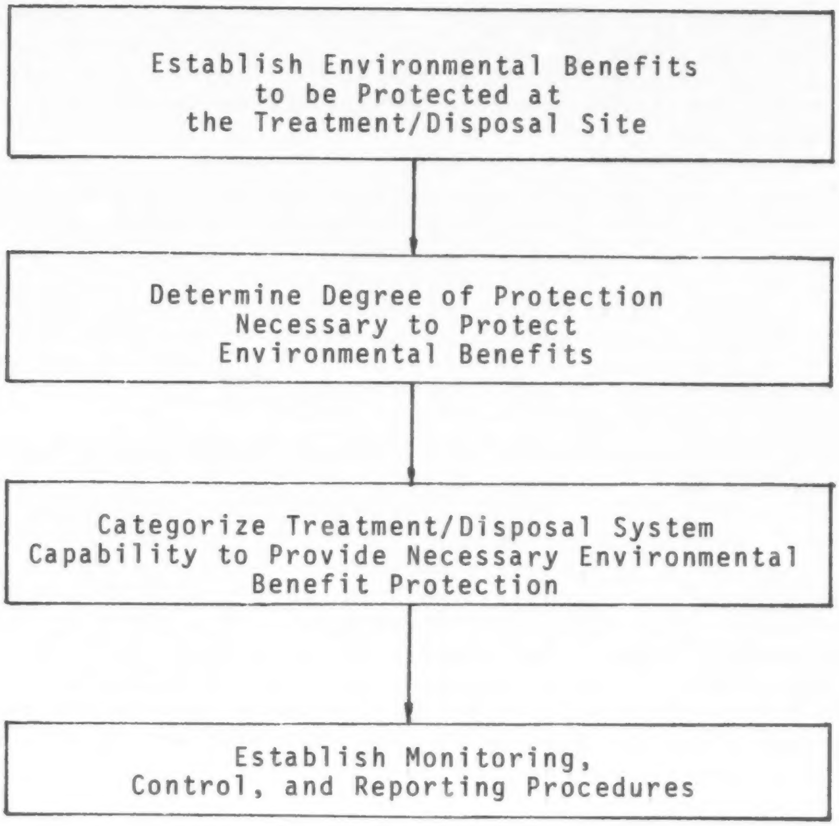
Establish Environmental Benefits to be Protected at the Treatment/Disposal Site
Determine Degree of Protection Necessary to Protect Environmental Benefits
Categorize Treatment/Disposal System Capability to Provide Necessary Environmental Benefit Protection
Establish Monitoring, Control, and Reporting Procedures

Figure 22. Stepwise Approach to the Proposed Regulatory System

1. Identification of the groundwater aquifers in the area which could be affected by migration of leachate from the disposal site. Each aquifer should be defined to the extent feasible in terms of depth, size, storage capacity, replenishment rate, and maximum withdrawal rate. It is recognized that hydrogeology is an inexact science; however, a qualified professional can utilize background information and field tests (test wells, seismic readings, etc.) to make his estimates.

2. Determination of the quality of the existing groundwater in each aquifer potentially affected by leachate from the proposed disposal site. Quality analyses should include normal chemical, physical, and bacteriological tests for potable water supplies.

3. Best estimate of the existing and/or potential beneficial uses of the groundwater in each aquifer potentially affected by leachate from the proposed disposal site. Existing and/or future probable usage could include the following categories:

   . Community water supply
   . Individual home/ranch/farm water supply
   . Agricultural irrigation supply
   . Industrial process water supply

Surface Water Resources

As previously stated in this report, FGD disposal sites constitute a major hazard to surface waters if there is a failure of the retention structure and the stored sludge escapes. Whether the proposed site poses such a danger can be evaluated on the basis of the following criteria:

- Distance from site to surface water(s)
- Elevation difference between site and surface water(s)
- Type of surface water(s), e.g., lake, river, etc.
- Present or projected beneficial uses of surface water(s)
- Volume and/or flow rate(s) of the surface water.

It is anticipated that this evaluation will not always be clear-cut, i.e., that there is a serious danger to valuable surface water resources in case of impoundment failure, or that no danger exists because of favorable topography and location.

Future Land Uses at the Site Location

As discussed elsewhere in this report, the load bearing capability of ponded unstabilized sludge is generally poor. With proper cover material, light recreational use is possible, but in essence the pond area is eliminated for higher use purposes. In many disposal site areas this situation may be acceptable, because the land has little projected value.

CATEGORIZE SITES ACCORDING TO DEGREE OF PROTECTION NECESSARY

General

At this point in the procedure, an estimate is made of the acceptability of the site for FGC sludge disposal based on natural site characteristics and the characteristics of the FGC waste. It is desirable to formulate a series of site categories based on possible beneficial uses. A simplistic site categorization system has been developed based only upon protection of groundwater resources, surface water resources, and future land use. Table 55 summarizes the seven categories of sites selected. They range from site category 1, where there is essentially no environmental benefit to protect, up to site category 7, which is unacceptable for FGC sludge disposal because no practical technique will adequately protect a valuable groundwater resource. Figure 23 shows a decision tree approach to disposal site categorization into one of the seven categories. The remainder of this subsection will discuss the use of Figure 23.

Decision Tree Approach

As shown in Figure 23, each of the decision points is based upon a site variable. These variables, discussed in Section IV, are listed below along with decision levels used in the decision tree:

1. Possible future land use
    - a. Possible urban or industrial development in the surrounding area in the reasonable future (excluding power plant use).
    - b. Little or no probability of development beyond range land or agricultural land in the surrounding land.

TABLE 55. PROPOSED CATEGORIZATION OF FGC DISPOSAL SITES

	Environmental Benefit Requiring Protection			Protection Method		
Site Category No.	Land Value	Surface Water	Ground-water	Sludge Pretreatment	Retention Dikes	Site Modification - Reduce Mass Transport
1	Low	No	No	No	Standard	No
2	Low	Yes	No	No	Extraordinary(2)	No
3	High	No	No	Stabilize(1)	Standard	No
4	High	No	Yes(3)	Stabilize	Standard	Yes
5	Low	No	Yes	No	Standard	Yes
6	Low	Yes	Yes	No	Extraordinary	Yes
7	Site unacceptable regardless of protection methods used due to impossibility of adequately protecting groundwater resource					

(1) It is assumed that stabilized sludge will not flow and poses no threat to surface water regardless of retention dike integrity.

(2) Dual dikes, supplementary interceptor pond, or other failsafe method of preventing escape of sludge if primary dikes fail.

(3) See narrative for discussion of pollutant mass transfer potential through soil.

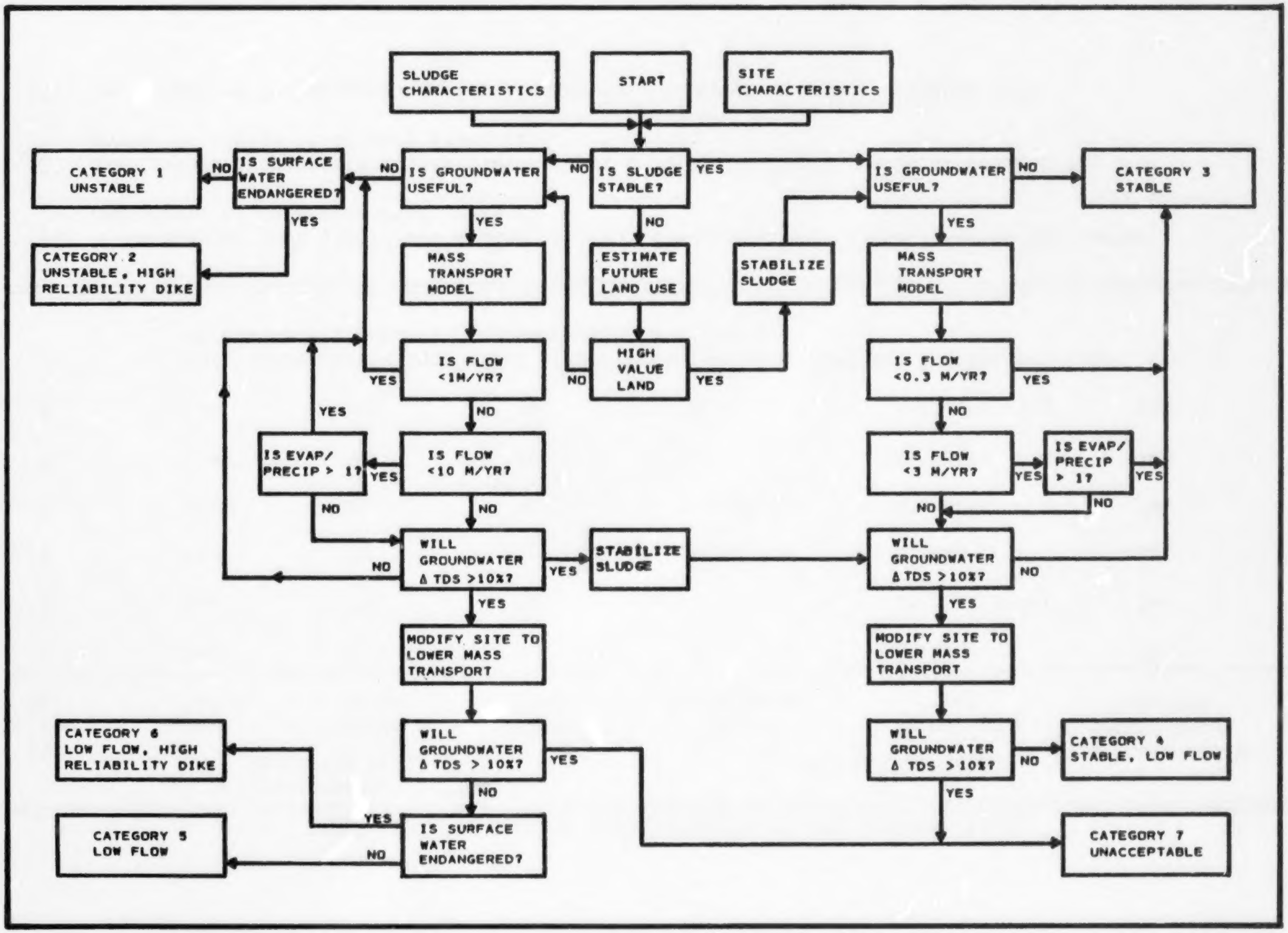
SLUDGE CHARACTERISTICS
START
SITE CHARACTERISTICS
IS SLUDGE STABLE?
YES
NO
IS GROUNDWATER USEFUL?
NO
YES
IS SURFACE WATER ENDANGERED?
NO
YES
CATEGORY 1 UNSTABLE
CATEGORY 2 UNSTABLE, HIGH RELIABILITY DIKE
MASS TRANSPORT MODEL
IS FLOW <1M/YR?
YES
NO
IS FLOW <10 M/YR?
YES
NO
IS EVAP/ PRECIP > 1?
YES
NO
WILL GROUNDWATER Δ TDS >10%?
NO
YES
STABILIZE SLUDGE
MODIFY SITE TO LOWER MASS TRANSPORT
WILL GROUNDWATER Δ TDS > 10%?
YES
NO
IS SURFACE WATER ENDANGERED?
YES
NO
CATEGORY 6 LOW FLOW, HIGH RELIABILITY DIKE
CATEGORY 5 LOW FLOW
ESTIMATE FUTURE LAND USE
HIGH VALUE LAND
NO
YES
STABILIZE SLUDGE
IS GROUNDWATER USEFUL?
NO
YES
CATEGORY 3 STABLE
MASS TRANSPORT MODEL
IS FLOW <0.3 M/YR?
YES
NO
IS FLOW <3 M/YR?
YES
NO
IS EVAP/ PRECIP > 1?
YES
NO
WILL GROUNDWATER Δ TDS >10%?
NO
YES
MODIFY SITE TO LOWER MASS TRANSPORT
WILL GROUNDWATER Δ TDS >10%?
NO
YES
CATEGORY 4 STABLE, LOW FLOW
CATEGORY 7 UNACCEPTABLE

Figure 23. Decision tree approach to disposal site categorization.

2. Groundwater resources

   a. The near-surface aquifers under the site contain potentially useful water.

   b. Existing near-surface aquifers do not meet useful standards and are not interconnected with potentially useful aquifers, or, even if the water quality is satisfactory, the quantity and potential pumping rates per well exclude economic use of the water (e.g., near-surface aquifers have a low permeability -- silty clay or clay with little sand and gravel).

3. Evaluation of natural protection to groundwater resources afforded by site geology and hydrology, if the groundwater is considered valuable

   a. Time constants -- Calculate the time necessary for migration of leachate over a 100 m distance.

      a_1. Time greater than 30 years (flow velocity less than 10^{-5} cm/sec)

      a_2. Time less than 30 years (flow velocity higher than 10^{-5} cm/sec)

      a_3. Time greater than 300 years (flow velocity less than 10^{-6} cm/sec)

   b. Rate constants -- Calculate the equilibrium mass transport of TDS out of the disposal site (see Section VIII and Appendix B for calculation approach). Estimate the probable rate of groundwater movement through the aquifer(s) affected (hydrology study). Determine increase over background TDS in the groundwater resulting from mixing with leachate.

      b_1. Rate and quality of leachate, at equilibrium flow rates, are low enough relative to ambient groundwater quality and flow rates such that the groundwater (assumed mixed) leaving the site shows a less than 10 percent (arbitrary number) increase in TDS. Calculations should neglect soil adsorption.

b_2. Rates will cause an increase in groundwater TDS of greater than 10 percent.

4. Surface water protection from catastrophic events
    a. Sulfite-bearing sludges can reach a water course should impoundment or pipe failure occur.
    b. Sulfite-bearing sludges cannot reach a water course following catastrophic release.
5. Site meteorology
    a. Evaporation rate from wet sludge exceeds precipitation rate minus runoff from specific site design
    b. Precipitation exceeds evaporation from wet sludge

The rationale for selecting the number shown in 1 through 5, above, is partially subjective. This subjective quality becomes necessary when one considers the following:

1. Zero impurity transport from the disposal site for infinite time is a physical impossibility;
2. The relevant time scale for pollutant movement has not been defined in either a legal sense or in terms of consensus in the scientific community;
3. Since zero degradation of groundwater over infinite time periods is impossible, what is acceptable degradation? (We have used a 10 percent change in TDS.)
4. The value to be placed on future land use versus current costs has not been defined either legally or socially.

Recognizing the subjective nature of these numbers, the following rationale can be given for each value shown:

- Potential land uses - If there is no prospect of the land being used for some purpose with a higher value than range or agricultural land in the next 100 years, the load bearing strength and associated physical properties of the completed disposal site are of lesser importance.
- Groundwater protection - If the groundwater is of low quality or inaccessible because of low extraction rates,

it cannot be classified as a resource needing protection.

- Mass transport rate - 0.3 m/yr. If the rate of pollutant movement is this slow, it can be considered insignificant (10^{-6} cm/sec flow rate).

- Mass transport rate - 3 meters/year. If the impurities have only moved 90 meters in 30 years and the meteorology is such that the site will dry out after closure (power plant life is 30 years or less), little movement will occur after closure and can be neglected.

- Mass transport rate - 10 percent contamination of mixed groundwater: Considering the variations in groundwater quality over short distances, it is believed that the 10 percent increase would be acceptable at virtually any site. The percentage is obviously an arbitrary number and at many sites a larger percentage increase would be acceptable.

- Surface water protection - It is not necessary to provide extra protection for surface waters if the sludge cannot reach the water upon accidental release. A release of this type would only create an unpleasant situation and not an ecological disaster.

The combination of these variables to categorize disposal sites was shown in Figure 23. This figure interrelates the site variables in such a way that environmental protection can be achieved without placing extensive and expensive restrictions on sites which naturally protect the environment.

ESTABLISH MONITORING, CONTROL, AND REPORTING PROCEDURES

General

Once the disposal site has been subjected to the above criteria, it becomes operational under the appropriate category and its restrictions. Monitoring, control, and reporting procedures should be specified for all FGD sludge disposal sites.

During the categorization procedure, the potential for environmental impact from several parameters was evaluated. These parameters included:

- Groundwater contamination
- Sludge in-place stability
- Catastrophic sludge release to surface waters

Groundwater Monitoring

The potential for groundwater contamination from sludge leaching is determined as part of the site evaluation. Input parameters include sludge leachate characteristics, soil and sludge permeability, hydraulic gradients, groundwater hydrology and quality, and attenuation and ion exchange capacity of the soil. These parameters together comprise the simplified mass transport model described in Section VIII. Therefore, the purpose of the monitoring program should be to confirm or contradict these projections based upon field sampling data.

As discussed in Section IX, the best chemical regulating parameter is total dissolved solids. The TDS "front" should precede all other trace metal detection in the groundwater due to limited attenuation of the common monovalent cations and anions. Limited theoretical knowledge of attenuation procedures makes TDS the simplest parameter to model and perform field comparisons with.

Present techniques for monitoring groundwater contamination are often inadequate. Regulations usually require the installation of sampling wells around the site perimeter and periodic analysis of samples from the wells to detect increases in background levels of various contaminants. The drawback to this technique is that the sampling wells are drilled to a depth below the groundwater table in order to reach saturated soil. There is no evidence of contamination until the leachate has reached the groundwater. At this point in time the leachate has already passed through the soil between the bottom of the pond and the groundwater aquifer and the situation is irreversible. Sampling techniques should be developed which measure the rate at which the leachate is leaving the disposal pond and passing through the soil between the pond bottom and the groundwater aquifer. Such techniques will provide early warning if theoretical calculations were incorrect at a time when preventative measures can still be implemented. It is beyond the scope of this report to define alternate sampling techniques; however, it is a universal problem which deserves research and development.

Accidental Spill Monitoring and Prevention

Procedures for monitoring spill potential are available for other specialized waste disposal/handling systems. These procedures can be readily adopted to FGD sludge disposal. Maintenance of impoundments for phosphate slimes is governed by the Rules of the State of Florida Department of Pollution Control (See Section XI). These rules govern inspection of dams and dikes during disposal and periodically following closure. Documentation of operations is also required. The control of sludge spillage from pipe failure is analogous to the monitoring requirements for oil handling and storage facilities. Under EPA

Regulations on Oil Spill Prevention (38 FR 34164, December 11, 1973), all aboveground pipelines and valves require regular examination to avoid spill events (Section 112.7, Spill Prevention Control and Countermeasure (SPCC) Plan). While not directly applicable to sludge due to the variety of storage, handling, and transportation alternatives, substantial technology transfer appears feasible.

In-Place Sludge Stability Monitoring

Several states currently use stability as one evaluation criterion but have not as yet developed a comprehensive definition for regulating purposes. Stability as it is used in current research refers to the sludge load bearing strength as a function of time and nature of the applied force (static vs. dynamic). For sites requiring stabilization for load bearing purposes, stability should be similar to that of the surrounding soil (nondegradation).

APPENDIX B

THE EQUATIONS OF MASS TRANSPORT

In Section VIII, it was shown that disposal site characteristics influence the rate at which FGD sludge contaminants are released to the environment. Adsorption, precipitation, and desorption effects on concentration terms in relation to overall mass transport have been under investigation by scientists. Soil scientists have applied mass transport theory to the migration of various ions through soils.

The present state of knowledge with respect to mass transport of contaminants through soils is not totally satisfactory, but this knowledge is advancing rapidly.

There are several approaches to describing mass transport of contaminants through soils and groundwater. The equations used to describe this phenomenon usually include a convection term and dispersion term. The convection term describes the movement of contaminants relative to the liquid flow velocity. The dispersion term accounts for the spread of contaminants with time due to the concentration gradient. The convection and dispersion terms have been combined into an overall mass transport equation in the EPRI study by Radian Corp. (Ref. 133). A discussion of this theoretical approach is appropriate here.

OVERALL MASS TRANSPORT THEORY

In the approach used by EPRI, the concentration terms are similar to those used in chromatography theory. The overall mass transport equation can be described as follows:

$$\frac{\partial C}{\partial t} + \left(\frac{1-\varepsilon}{\varepsilon}\right) \frac{\partial Q}{\partial t} = - \bar{\upsilon} \nabla C + D \nabla^2 C \qquad (1)$$

where, C = fluid-phase solution concentration

Q = solid-phase concentration per unit volume of solid

$\bar{\upsilon}$ = interstitial fluid velocity

t = time

ε = void fraction

D = dispersion coefficient

∇ = gradient operator

∇^2 = Laplacian operator

The implicit assumptions in the formulation of the above mass transport equation are (1) that the dispersion terms are not a function of concentration, and (2) that any uniformities in the interstitial velocity term are accounted for in the dispersion term.

If the solid phase concentration is equal to a constant times a liquid phase concentration, the following relationship holds true:

$$Q = KC \tag{2}$$

where:

K = distribution coefficient (which may be a non-linear function of C)

This is only valid for concentrations well below the solubility limit or site adsorption capacity.

Utilizing equation (2) and assuming local equilibrium exists, it is possible to define a retardation parameter R as follows:

$$R = 1/\left(1 + K\left(\frac{1-\varepsilon}{\varepsilon}\right)\right) \quad * \tag{3}$$

This retardation parameter has been adopted from chromatography theory. It is the same parameter utilized in the theory associated with trap diffusion in solids. This retardation parameter provides an effective method of dealing with the

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*The definition of this retardation parameter from random walk theory is derived in several fashions in the literature (Ref. 21 , 165). It has also been defined as

$$1 + \left(\frac{1-\varepsilon}{\varepsilon}\right) K$$

rather than the inverse used in this narrative (Ref. 123). This difference in terminology definitions is important when works are reviewed in this subject.

fact that a moving contaminant spends part of its time in the liquid and part of its time on the immobile solid phase. The partitioning coefficient provides an idea of the relative time spent in either of the two phases, with the solid phase being stationary. It is assumed that the contaminant does not make forward progress while it is spending time on the solid.

There are also implicit assumptions of no precipitation in this formation of the transport equation. They mean that this equation will predict faster migration than would be observed in field situations where precipitation occurs. In the proper formulation of this equation, the constant K is a function of C_i, T, and the soil (where C_i is all the ions in solution, expressed in terms of activities).

Using Equation (3), Equation (1) can now be rewritten in the following form:

$$\frac{\partial C}{\partial t} = -R\bar{\upsilon}\nabla C + RD\nabla^{2} C \qquad (4)$$

The above overall mass transport equation contains two terms. The first of these, $-R\bar{\upsilon}\nabla C$; is the convection term, which depends upon the velocity of the liquid flowing through the interstitial voids in the material. The second, $RD\nabla^{2}C$, is a dispersion term that is related to molecular diffusion, multipath dispersion, fluid-phase mass transfer, interparticle diffusion, adsorption phenomena, and other factors that tend to disperse the concentration profile.

The velocity term $\bar{\upsilon}$ in Equation (4) is related to the permeability of the material through which the fluid is passing according to Darcy's Law. It should be noted that the velocity in Equation (4) is velocity through the interstitial space and not the overall average velocity (superficial velocity) as generally computed from Darcy's equation. Therefore, Darcy's equation must be modified as follows to include the void fraction term:

$$\bar{\upsilon} = -\frac{k}{\varepsilon}\nabla\cdot\Phi \qquad (5)$$

where:

Φ = the hydraulic potential = $(P + \rho g h)$

k = hydraulic permeability (includes viscosity term)

As shown earlier in this document, k is not necessarily constant, and may depend on $\nabla\cdot\Phi$ or the degree of saturation of the material.

Equations (1), (3), and (4) can be written in a more general form, in which the effective dispersion coefficient (D) and the retardation coefficient (R) are both a function of concentration. In this form, the dispersion term entering into Equation (4) would be nonlinear ($\nabla \cdot RD \cdot \nabla C$ rather than $RD\nabla^2 C$). As shown in Section VIII, the dispersion term is insignificant to overall mass transport for the times and distances relevant to stabilized sludge disposal. Therefore, these nonlinear effects and subtleties in the equations are of no significance.

In attempting to show the relative magnitudes of the convection and dispersion terms in Equation (4), it is useful to look at each term individually. In the dispersion term, the value for R will range from virtually 0 to a maximum of 1. The maximum case of 1 is obtained for zero adsorption; consequently, there is no retardation. Values of R less than 1 are achieved when this impurity is significantly adsorbed by the soils through which the liquid passes. The value of R for anions is typically on the order of 1, with a corresponding partitioning coefficient near 0. However, the high cation exchange capacity of many soils (in particular, clays or high organic soils) causes the cations to have much smaller values of R and correspondingly higher values for the partitioning coefficient. Typical R values for multivalent cations are on the order of 10^{-3}.

The dispersion term D in Equation (4) is comprised of two classes of terms. The first class includes terms that are independent of velocity. These terms correspond to the diffusion through the liquid phase that would be experienced for the ions in question, unaffected by velocity, adsorption, or desorption. This conventional diffusion term is the same as the diffusion coefficient in liquid for the ion in question. However, the term is corrected for the void fraction effects resulting from the occupation by solids of much of the volume. The term is also corrected for a corresponding increase in effective path length. This increase is due to the fact that the ions must circumvent the particles. These correction factors may decrease the effective diffusion coefficient by, at most, a factor of 10 over that measured in a static all-liquid system.

The second class of terms entering into the dispersion term is produced by the velocities of flowing interstitial liquids. This class of terms includes, among others, multipath dispersion, fluid phase, mass-transfer kinetics, interparticle diffusion, and adsorption and desorption kinetics. The multipath dispersion contribution can be visualized by observing that some pores in the soil are larger than others and would have a higher interstitial velocity. Therefore, some parts of the stream will flow at different velocities than other parts. As a result, any concentration front would tend to be dispersed.

At this point, it should be noted that the basic theory associated with chromatography has derived functional forms for plate heights and has derived other related phenomena for the velocity-dependent terms. These velocity-dependent terms are the primary determinants of the dispersion characteristics for chromatography theory. For the flow of fluids from the disposal pond operation through soils, very low velocities are encountered.

At such low velocities, the diffusive component of the dispersion coefficient may be the dominant term. This will depend upon the actual velocities and specific geological conditions in question. As a result, the correction factors that must be applied to the known liquid-phase diffusion coefficients for the ions in question become more important for soil migration than for chromatographic theory. This correction factor will be different in soils than in a chromatograph, which has a fairly open and well-defined packing. As previously mentioned, this correction factor would have an expected value range of 0.1 to 0.3, rather than the .6 characteristic of chromatography.

These velocity-dependent terms in the dispersion depend strongly upon the uniformity of the geological conditions. Where the flows are highly nonuniform, such as in the case of cracked rock, these terms may be thousands of times larger than they are in uniform conditions, such as in sand.

LABORATORY ANALYSIS OF MASS TRANSPORT

The interplay between diffusion and convection terms is important when evaluating the environmental impact of FGD sludge disposal, as discussed in Section VIII under site characteristics. Convection is the dominant term in untreated sludge leaching, provided the underlying soil is fairly permeable. Diffusion can limit leaching of highly soluble salts and certain trace metals from stabilized sludges.

While modeling the convective cases is fairly straightforward, research efforts are continuing to evaluate diffusion-limited leaching from stabilized sludges. Four different approaches to leaching stabilized sludge have been employed thus far, each one of which combines both diffusion and convection but with one or the other possibly dominating the mass transport. These methods are:

1. Pressurized flow of small volumes of water or leaching solution through stabilized sludges, with results giving some indication of soluble salts depletion as a function of pore volumes leached (Ref. 96);
2. Surface washing of stabilized sludge in a packed column, representing rainwater and groundwater washing

of the sides of a sludge monolith, sich as a stable landfill (Ref. 162);

3. Agitated washing of a sludge plug, representing surface runoff from a stable landfill*;

4. Elutriation of crushed, stabilized sludge, representing the solubility limits of the various sludge contaminants (Ref. 96).

Approaches 1 and 4 are representative of convective leaching of stabilized sludge, while 2 and 3 represent primarily diffusion-limited leaching. The latter approaches most closely represent the mechanics of leaching within a stabilized mass.

In interpreting diffusion-limited experiments using approaches 2 and 3, it is useful to construct a conceptual model of what is happening. Assume that the solid material is made up of an insoluble, interconnected matrix that surrounds an interconnected group of semisoluble materials, highly soluble materials, and voids filled with either air or liquid. After initial removal of loose material from the surface, the interconnected matrix material is chemically and physically stable. The group of semisoluble materials would include components such as $CaSO_4 \cdot 2H_2O$, $CaSO_3 \cdot 1/2\ H_2O$, CaF_2, and other components, whose solubility limits and concentrations in the solid phase indicate that a solid phase will exist when the sample is water saturated. The group of soluble components would include materials such as Na_2SO_4, NaCl, $CaCl_2$, etc., whose solubility limits and concentrations in the sample would allow them to be in solution in the liquid-filled interstitial volume under saturation conditions.

The limited solubility components will behave differently than the highly soluble components under different experimental conditions. Hence, one cannot discuss the problem from the standpoint of TDS alone. The individual components making up the TDS must be looked at separately.

The limited solubility components have a very large reserve of solid phase near the surface, with relatively short diffusion distances. If the rates of achieving local equilibrium between the interstitial liquids and the solid phases are fast, there would be a denuded zone near the surface where no soluble phase of the component exists. Clearly this assumes that: (1) the matrix does not fall apart when the soluble phase is removed; (2) there are no driving forces for liquid movement through the matrix; and (3) diffusion in the liquid phase is rate controlling.

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*Personal communication with Steven I. Taub, I U Conversion Systems, December 28, 1976.

The highly soluble salts will behave differently than the limited solubility salts. The highly soluble salts, such as $NaSO_4$, will be diffusing from further inside the specimen and will not have the effective reserve of a large-volume solid phase. Once the sample is fully saturated, one can assume that all these salts are in the interstitial liquid phase. If there is 2 percent Na_2SO_4 in the sample and the sample contains 10 percent water-filled voids, one would expect this interstitial water to contain 200,000 ppm of Na_2SO_4.

These solubility differences manifest themselves in the results of approaches 2 and 3. Approach 2 is a long-term experiment, so the system would be expected to be near equilibrium for all major components within the specimen (but not for some heavy metals which may be absorbed). Since these experiments are near equilibrium, they will provide information with respect to contaminants that may be tied up chemically or physically in a manner that prevents them from achieving equilibrium with the interstitial liquids (i.e., co-precipitation, incorporation as substitutional impurities in insoluble solid phases, etc.). The system in approach 3 would be near equilibrium for limited solubility salts with large reserves in the solid phase, but would be near nonequilibrium for highly soluble salts. If the data from approaches 2 and 3 on the components making up the TDS were compared, one would expect to find similar results between 2 and 3 for the $CaSO_4$ and different results for $NaSO_4$, NaCl, etc., and possibly for heavy metals.

There are several factors encountered in practice that can effect the analysis. The percentage saturation as a function of position within the sample would cause the effective diffusion coefficient to be a function of position. Adsorption/desorption phenomenon on surfaces with the matrix would reduce the effective diffusion coefficient (this may be very significant for heavy metals). Details of the experimental procedures will affect the boundary conditions used in the derivations of Equation (4) and may dictate that a different solution be utilized. The various species that are contained within the sample do interact; there will be effective solubility constants in the various components, which are functions of position and composition within the sample. Another complicating factor may be slow dissolution kinetics associated with some solid phases, which may control the overall rates.

Therefore, it can be concluded that both approaches 2 and 3 have some value in gaining an understanding of leaching from stabilized sludge. The mathematics can only estimate what will occur in the field. Laboratory studies and site monitoring are essential to confirming the estimates.